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IRRIGATION, ROADS, AND BUILDINGS

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HIS LONG-CONTINUED AND SUCCESSFUL WORK IN

RECONSTRUCTING AND DEVELOPING THE BRITISH EMPIRE.

NOTES ON
IRRIGATION, ROADS, AND BUILDINGS
AND ON THE WATER SUPPLY OF TOWNS

BY

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WITH 222 FIGURES.

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PREFACE.

Many engineers for their own guidance make notes of general matters connected with their practice, but few publish anything except in professional papers dealing with specialised subjects, so that much of their practical knowledge dies with them and does not benefit their successors, who have thus to gain unaided their own experience, and often acquire it by the slow and expensive process of trial and error. For many years I have collected notes, reports, circulars, etc., with a view to the preparation of this book, which, I trust, will be of use to my younger professional brethren who have to continue the development of the countries in which they labour by the execution of public works that benefit the inhabitants thereof, either by their aggregate number or individual importance. Some of the prescriptions therein may appear obvious, but have been entered on account of observed mistakes. My own experience has been obtained in a service of over thirty years under the Governments of Bombay, India, the Transvaal, and Ceylon. The Bombay Presidency (which extends along the western coast of India as a comparatively narrow strip 1,200 miles long) offers an epitome of the irrigation works of India. In Sind, in the north, are a considerable number of large inundation works and one important modern canal, while others are under contemplation; in the centre are many large storage works with their canal systems; and in the south are numerous ancient minor reservoirs, or "tanks." The distribution of these classes of irrigation in India, generally, is similar. I have chosen for my title "Irrigation, Roads, and Buildings," the name of the branch of the Indian Public Works Department in which my service was chiefly spent.

"Irrigation" is discussed at considerable length, as the classes of its work are many and the conditions under which they have to be constructed and maintained are varied. This Part begins with "irrigation" and ends with "civilisation"—an illustration of cause and effect. The other Parts are treated shortly.

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"Water Supply of Towns," although not a branch of irrigation, has many features in common with it, particularly in regard to storage and consumption ; it differs from that in the necessity for obtaining a sanitarily pure supply and in methods of distribution. There are many books and papers on this subject, and this Part does not pretend to be original. I trust, however, that I have arranged the descriptions of the various matters dealt with in a simple and easily intelligible manner.

"Roads" is practically limited to ordinary lines of communication in rural tracts, and this Part describes only generally the construction of more complicated modern surfaces in urban areas.

"Buildings" is confined to Government residential and inspection houses in the tropics, but the general principles described are applicable to other structures : this Part, however, does not attempt to be an architectural treatise.

The combination of these subjects in one volume is, no doubt, unusual, but in the East, where there are few specialists, and most are general practitioners, an engineer may be concerned with all of them in his career, and occasionally at the same time. Even in the West town engineers may be required to carry out works connected with the three last named.

Throughout the book the arrangement proceeds from the general to the particular ; principles are first enunciated and their practical application follows. The different types of works are described in the order of their occurrence, from the head downstream to the tail of the systems. The book is divided into Parts, chapters, articles, and paragraphs, numbered for easy reference, and to allow of cross-references, so as to make the treatment of each subject more complete and to save repetition. Wherever practicable, the argument takes the form of notes in order to render the treatment of the different matters dealt with more concise and prominent.

The illustrations have been drawn to suit the size of the book and to scale where necessary ; they have been reproduced by Messrs. John Swain and Son. About two-thirds of them are original, although many of these follow ordinary type designs with certain modifications. Numerous dimensions and descriptive notes are given so as to make the sketches easily intelligible. A considerable number relate to small works, as these will be the ones which have chiefly to be constructed ; the designers of large schemes will have to guide them their own experience and the plans of existing similar ones. The principles involved in the proper treatment of both small and large constructions are the same. There can be no better training for the young engineer than designing even small works and improving their types in accordance with such principles.

Naturally, I have not depended solely upon my own experience, but in connection with that have availed myself of the books and papers detailed in the "Bibliography." I am indebted to all the Authors named therein, and particularly to Sir Francis Spring, Messrs. Buckley, Flynn, Parker, and Professors Turneaure and Russell. The books are so well known that they do not need any commendation from me; they contain descriptions and illustrations of important constructed works, and give all the mathematics, formulæ, tables, and statistics required by a designer. This book, in which such practically do not appear, deals with general principles and constructive details, and may, I hope, be found useful as supplementary to those treatises. The Indian Government papers are less well known, but are extremely useful as descriptive of matters connected with irrigation, which has been developed further in India than elsewhere. As the progressive development of irrigation deserves thus to be recorded, it is unfortunate that the issue of these papers has been curtailed. Further papers would be improved by some compression and the addition of abstracts summarising the conclusions arrived at.

This book was written during the continuance of the great World-War. The physical conditions which affect irrigation have had a predominant influence on the various campaigns. Rivers—the Marne,[1] Somme, Piave, Danube, Tigris, and many others—have given their names to famous battles; watersheds (mountain ridges) have had great military value, while deltas have caused peculiar difficulties. The map of the progress of the 1918 re-conquest of France resembled the plan of erosion by an alluvial river; climatic changes have had much effect, and man's dependence on agriculture has been emphasised. Good water supply has been recognised as a matter of the first importance, and was arranged for in all fields. Roads have been constructed for great mileages, and in mountainous areas have enabled heavy artillery to be conveyed to heights previously never trodden by the foot of man. Buildings of a temporary nature have been erected in large number for military purposes, but alas! many irreplaceable artistic structures of other days have been obliterated or extensively damaged.

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[1] Figures 108 and 109 illustrate old works on this river, which has twice been the scene of the turning of the course of the world's history during this prolonged conflict.

After War has come Peace—a peace during which the world must be re-born and its sound development ensured, or the War will be a final loss. Irrigation must be promoted, and has indeed been increased in Mesopotamia during the campaign; both young and old States will require new water supplies and many roads and buildings. If this book proves of assistance to those who will have splendid opportunities of constructing these public improvements, I shall be amply repaid for my labour on its preparation, and in that hope I publish it as my contribution to such development.

W. L. STRANGE.

WORTHING,
10*th January*, 1920.

NOTE.

All costs quoted are at pre-War rates.

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GLOSSARY OF ABBREVIATIONS AND INDIAN WORDS.

F.S.L. = full-supply level.
H.F.L. = high-flood level.
L.F.L. = low-flood level.
L.W.L. = low-water level.
R.L. = reduced level.
T.W.L. = top-water level.
W.L. = water level.
Cusecs = cubic feet per second.
D.S. = downstream.
U.S. = upstream.
B.H.P. = brake horse power.
I.H.P. = indicated horse power.
N.H.P. = nominal horse power.
C.I. = cast iron.
D. (or dia.) = diameter.
M.S. = mild steel.
R. (or rad.) = radius.
S.R. = steel rolled (beam).
S.W.G. = standard wire gauge.
T. = thickness.
W.I. = wrought iron.

Bandhárá = an intake weir.
Bár = high land bordering the Khádir.
Bund = an earthen embankment.
Ghát = a mountain range.
Kankar = nodular hydraulic limestone.
Khádir = low-lying riverain land.
Kharif = the season from February 15th to October 14th.
Monsoon = the rainy season.
Muram = disintegrated trap rock.
Nulla = a drainage watercourse.
Rabi = the season from October 15th to February 14th.
Rupee = 1s. 4d.
Tank = a storage reservoir.
Usar = efflorescence of alkaline (sodium) salts.

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UNIV. OF CALIFORNIA

IRRIGATION, ROADS, AND BUILDINGS.

PART I. IRRIGATION.

CHAPTER I.

INTRODUCTORY.

1. Preliminary.

(*a*) *Definition of Irrigation.*—Irrigation is the art and practice of supplying water artificially to land for the growth of crops, which, otherwise, could not be assured. From the point of view of art it is a branch of engineering, and from that of practice, one of agriculture.

(*b*) *Irrigation supplementary to Rainfall.*—Plants require for their growth proper weather conditions of heat, light (actinic rays) and moisture. In irrigating countries the first two are abundant and do not need to be supplemented. The last-named is there frequently deficient, and is the only one which can be supplied artificially on a large scale, and that is done by irrigation.

Irrigation is carried on in many countries, but chiefly in tropical and sub-tropical ones, where the rainfall is either deficient, or comes at unseasonable times or irregularly, and it attains its greatest development in lands which are practically rainless, as there it becomes an absolute necessity for agriculture. In hot climates, even when the total rainfall is abundant, irrigation is required for certain crops, such as rice, owing to the uncertainty of the rainfall and the need of a constant supply of water; other crops which can there be grown without irrigation usually have their yield increased by its application. Practically rainless countries where water can be supplied artificially have the great advantage that the growth of crops is wholly under control, and is not liable to be injured by unseasonable falls of rain. Rainfall is, however, generally of advantage by reducing the amount of water which has to be supplied artificially.

(*c*) *Benefits of Irrigation.*—Irrigation aids the general development of a country by utilising the valuable national asset of the water available. The section of the population directly benefited by it cannot advance in wealth and purchasing power without profiting other sections. Irrigation adds to the food supply and maintains a large population on the land in increased prosperity. In countries liable to famine it affords the best security against the effects of drought (during periods of which it confers its greatest benefit), and works for its extension form the best means of employment of those who have to be relieved during seasons of scarcity. When supplied to semi-civilised lands it turns turbulent and non-productive populations into peaceful and industrious ones.

In India it is calculated that the annual value of the crops there grown under irrigation is at least equal to the capital cost of the works supplying them with water. The intrinsic value of irrigation water naturally varies with the season; it is greatest by unit of volume in years of drought, but in years of plentiful rainfall the water goes further, and thus has a larger total value. The value of irrigated crops is greater than that of unirrigated ones, but as the former require better soil and cultivation and suitable climate, this increase in value is not wholly due to the means of irrigation afforded. The financial test of the value of irrigation works is not, however, the only one to be applied to them—consideration should be had to the indirect benefits of increasing thereby the wealth of the country as a whole, the prosperity of the agricultural community, the amount of railway receipts, trade, etc., and of reducing poverty, disease and crime.

(*d*) *Division of Supply available.*—As rain is the original source of water for irrigation, the supply from artificial works generally varies with the rainfall, and the issue of it has to be regulated accordingly. In ancient times the supply was therefore distributed, not by definite quantities, but by shares of the amount available. In modern times (Art. **23** (*b*)), especially during periods of deficiency, the practice is practically the same, although on certain works the distribution is by fixed quantities during ordinary seasons. The system of issue of water by measurement (Art. **26** (*c*)) is best adapted to temperate climates where the quantity of available supply in different years does not vary greatly; in tropical countries, where the fluctuations of such supply are great, fixed rates of issue cannot so easily be adopted, but must be modified by the principle of shares. The necessity for sharing the water available makes irrigation essentially a matter of co-operation, as all members of the irrigating community have interests in common.

2. Definitions of Terms.

In this book the meaning of certain terms employed is as follows :—

(i) *Alluvial soils* are those which have been deposited by the agency of the rivers which now are the source of their water supply. The country thus formed exists in large flat plains generally characterised by an absence of hard materials for foundations and construction; the river beds are usually of deep sand of varying degrees of fineness; and the rivers flow in comparatively shallow troughs, and often have not permanent courses. A canal irrigating such country is here termed an *alluvial canal.*

(ii) *Non-alluvial soils* are those which have a non-fluviatile origin, or have suffered geological change subsequent to their deposition. Even when the country in which they exist has plains, these are of lesser extent than alluvial ones; the land surface varies considerably from flat valleys to steep hill slopes; hard materials are generally available for foundations and construction; the river beds are often hard and sometimes of rock, and the courses of the rivers are permanent. A canal irrigating such country is here termed a *non-alluvial canal.*

(iii) *Dams* are structures generally of masonry or earthwork, and of considerable height, which are raised for impounding and storing water, and are designed so as never to be topped by the stored water.

(iv) *Weirs* are usually masonry, timber, or dry-stone structures built across rivers, which are designed to allow flowing water to pass over their crests—they are mostly of small height, but some are high.

(v) *Storage Weirs* are those which impound and store water by their unaided height or by the addition of raised temporary or movable crests.

(vi) *Diversion or Intake Weirs* are works which serve only to raise the water to a certain level and to divert the flow of main streams into the irrigation canals led from them. They may be converted into storage weirs by the addition of raised temporary or movable crests.

(vii) *Pick-up Weirs* are structures built across tributary streams so as to impound their flow and so as to carry canals beyond them.

(viii) *Waste Weirs* are escape channels for floods which cannot be stored, and are provided for reservoirs to ensure the safety of their dams.

(ix) *Canals* are the main lines of irrigation systems ; they lead direct from the sources of supply and feed the minor lines forming the distribution systems.

(x) *Distributaries or Branch Canals* are the next larger lines of the systems ; they pass the water from the canals to the "minors." In Upper India they are known as "rajbahas."

(xi) *Minors or Sub-branch Canals* are smaller channels led from the distributaries to supply the watercourses. These three classes of channels in India are constructed, maintained, and controlled by the State.

(xii) *Watercourses*, or field channels, are the very small channels which actually convey the water on to the fields. In India they belong to the irrigators, and are generally constructed and maintained by them, unless by agreement the State attends to the channels at the expense of the owners.

(xiii) *Percolation* is water which by the action of gravitation passes under or above ground from the source of supply, through more or less open soils or fissures, and appears visibly in the vicinity or in neighbouring wells or drainage channels. "Leakage" is another name given to percolation.

(xiv) *Seepage* is water which by the action of capillary attraction passes underground from the source of supply, through close soils, and does not appear visibly in the vicinity, e.g. the return of water underground from irrigated land back to the river supplying the system, either directly or down its tributaries.

(xv) *Secretion* is the water which is required initially to moisten the bed of a reservoir or a canal or irrigated land, and does not re-appear, being eventually dissipated by evaporation.

(xvi) *Loss by Evaporation* is caused by the action of sun and wind on surfaces of water or moist land and on vegetation (Art. 17).

(xvii) *Loss by Absorption* is the total loss caused on irrigation works by secretion, percolation, and seepage, but does not include secretion on and seepage from the irrigated area (Art. 18). In the Punjab loss by evaporation from canals (which is comparatively small, and does not exceed 15 per cent. of the total) is included in this. In reservoirs in India the total loss is said to be due to " evaporation and absorption," but the amounts of loss on each head are not usually shown separately owing to the difficulty of measuring the constituent losses.

(xviii) *Hydraulic Gradients.*—Four varieties are described on the pages noted in brackets against them, namely, those of :—earthen dams (163) ; river embankments (401) ; sand (436) ; and alluvial weirs (436).

(xix) *The Irrigation Points of the Compass.*—Irrigation works being concerned with the flow of water, it is clearer to define the position of the works, or portions of works, with reference to that flow, thus—upstream and downstream, right bank and left bank. For the first pair of terms are sometimes used " front and rear " or " inner and outer," which expressions are less definite, as they depend upon the position assumed by the observer. For the second pair of the adopted terms the usual points of the compass—north, south, etc.—are less significant. The expressions " right " and " left " are invariably allocated to the banks which are on those sides of a river when the observer has his back to its source.

(xx) *Other Definitions.*—The following terms are explained in the pages entered in brackets against them :—

1. *General.*—Hydrographic district (6) ; duty (32) ; contraction, complete or suppressed (108) ; riparian rights (533).

2. *Miscellaneous.*—Water table (26) ; afflux (53) ; gauging run (110) ; flume (110) ; velocity of approach (108) ; piping and fountaining (438).

3. *Alluvial Rivers.*—Bar or crossing (316) ; cut-off (319, 337) ; erosion (325) ; scour (329) ; swirl (330) ; horse-shoe bend (337) ; avulsion (337) ; afflux (338) ; reservoir capacity (339) ; delta (340) ; " thalweg " (344) ; " attraction of banks " (345) ; pocket (380) ; silt classification (407) ; " effective size " of sand (432).

4. *Canals.*—Loss in transit (27) ; " retrogression of levels "

(238); "wire-drawing" (288); critical mean velocity (411); silt attraction (408, 464); parallel distributary (518).

5. *Earthen Dams.*—Adhesion or cohesion (160); shrinkage of earthwork (173); free-board (173); breaching section (178).

6. *Storage.*—Flood-absorptive capacity (49); yield (98); run-off (99); storage capacities (138); temporary storage (142); silt classification (138); "equivalent catchments" (145, 218).

7. *Works.*—Submerged dam (308); divide wall (445); "reversed filter" (449); rising sill (472).

3. Hydrographic Districts.

(*a*) *Definition.*—A hydrographic district may be defined as one consisting of the whole of the surface catchment area, or gathering ground, of the main river draining it (or of the section concerned thereof) including the catchments of its tributaries. It is bounded by the watersheds which divide it from the catchments of neighbouring rivers or streams. The whole of the rainfall which runs off from it, unless part of it is artificially diverted (thus constructively decreasing one natural catchment and increasing the other) and except that portion which is lost by evaporation and absorption, eventually reaches the point where the river or stream crosses the downstream boundary of the district. Conversely, any rain falling outside the bounding watershed has no effect on the flow within the district except in the rare cases where a surface catchment has an underground connection with another. The size of a hydrographic district may thus vary from the catchment area of a large river to that of a small runnel. For the practical purposes of administration, however, it is necessary that the district should be arranged to be of some size, and that the size should have reference to the irrigation and other interests involved. Thus, in a thickly populated and well-watered area it would be advisable to make a hydrographic district smaller than would be desirable in a tract of country with few inhabitants and only small irrigation works.

(*b*) *Other Divisions of States.*—A hydrographic district is therefore a strictly physical division so far as water is concerned, for Nature has ordained the way in which the run-off from the land shall find its way to the sea, and any interference with her arrangements must tend to create difficulties. Irrigation is, however, not the sole concern of man, and thus the boundaries of States have generally been fixed on other than hydrographic considerations. From the point of view of irrigation, one of the chief mistakes thus made is that rivers have often been taken as these boundaries because they are clearly marked lines of separation, and are usually considered to have great military value. Some authorities,[1] however, now hold that that value does not exist in modern times when the means of crossing have been so much improved. A river running through a fertile plain (itself a physical unit) attracts to its banks large populations, which in time of peace, having many mutual interests, develop their inter-communications (which are easily established in such an area), and thus facilitate movement in time of war. It is therefore considered by these authorities that a better military boundary is afforded by a high tract devoid of population and means of traffic, such as a steep and barren watershed or mountain range, which effectually separates the sections on each side of it. If this view is correct, a hydrographic boundary is also the best political and military one.

(*c*) *Administration of Districts.*—It is naturally very difficult to affect any change of boundary between neighbouring States in order to improve the conditions of irrigation and internal navigation, but it is easy and advisable to divide an irrigating country into hydrographic districts, each having irrigation interests in common. As irrigation affects other concerns, it is desirable that the boundaries of the districts should correspond as closely as is practicable with the existing divisions of the country. In India the boundaries of village lands are often fixed on watersheds. Every such district should be placed under one irrigation officer, who can thus be held responsible for the management and development of irrigation within it, without having to consult engineers of his own rank.

4. Hydrographic Survey.

(*a*) *General Remarks.*—The irrigation engineer should have a thorough knowledge of the amount of water with which he has to deal; otherwise he must perforce work in the dark.

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[1] "Frontiers," by C. B. Fawcett, B.Litt., Clarendon Press, 1918; "Boundaries in Europe and the Near East," by Col. Sir Thomas H. Holdich, K.C.M.G., Macmillan, 1918.

If he is over-sanguine in his anticipation of the yield of a catchment or river, he may design a reservoir so large that it will not usually fill completely, or a canal which will not generally flow full, and will thus incur expenditure uselessly. If he is unduly cautious in his calculation of that yield, he may construct works of too small a size to utilise the water available, and the country will suffer by the resulting reduction of acreage under irrigation. Again, if he over-estimates the maximum discharge of a flood, he will provide escapes for passing it off of unnecessary dimensions and cost; if he under-estimates it, he will run serious risks of damage to the works and to other concerns. Thus the ascertainment of correct hydraulic data will conduce both to economy and safety in designs, and the cost of obtaining the data may be many times covered by the savings consequent on their acquisition.

(*b*) *Considerations in Respect of Observations.*—The primary consideration in regard to observations is that they should be accurately made and recorded in such detail that they can be utilised hereafter by others, even if these, with the advance in scientific knowledge, may possibly make use of the data thus obtained in a way different from that originally done. Next, the observations should be numerous, and should be continued for as long as possible, so that a complete idea of the problems to be solved may be gained. Inaccurate observations are not only useless, but may be misleading, and a few isolated ones may not be truly representative of the actual conditions to be met, seeing that abnormal hydrographic phenomena often occur at long intervals, but must be provided for by the works constructed to deal with them.

(*c*) *System of Observations.*—To entrust the making and recording of observations to the ordinary district staff will probably lead to the employment of untrained observers engaged on numerous other duties which may require most of their time. Moreover, that staff will be liable to transfer for reasons other than those connected with hydrographic survey, and the all-important continuity of the observations may thus suffer. It is therefore far better to engage a special staff to make these observations accurately, and, if necessary on account of expense, to reduce the number of the observations. If such a staff is financially not practicable, at least a special scientific officer, who might be known as the Hydrographic Surveyor, should be appointed so as to direct operations conducted by the ordinary district staff, and so as to introduce and maintain a uniform system of accurate observation and record. The observations to which he will have to attend will include those connected with—

Rainfall ;
River flow ;
High-flood discharge ;
Reservoir replenishment and losses by silting, evaporation, etc. ;
Irrigation supplies and losses in transit ;
Percolation and seepage.

Even in non-irrigating countries a hydrographic survey is for many interests as useful as a topographic survey. To secure impartiality, a series of observations carried out in the same way by a trained staff, and an easily available record, it is also advisable there to have the survey conducted by a Government department.

5. Flow Irrigation.

When water can be delivered by gravitation on to the land, irrigation is said to take place by flow ; the largest areas are thus irrigated under canals and reservoirs. The disadvantages of this form are that it may lead to an extravagant use of water whereby the irrigated area is reduced in extent below what it should be, and water-logging of the soil may take place so as to render the land unculturable, or make necessary the additional expense of drainage. It is therefore the duty of the engineer to regulate supply and prevent an excess use of it. The advantages of flow irrigation are that its cost to the cultivator is a minimum one ; the irrigated area can be concentrated and the cost of supervision reduced ; and increased discharges following scanty supply can best be utilised. It is this form of irrigation which can with most advantage be developed by engineering science, and it is therefore chiefly dealt with in this book.

6. Lift Irrigation.

When water has to be raised artificially so that it may be delivered on to the land, irrigation is said to take place by lift. Such irrigation is practised for high lands bordering canals and on the margins of the backwaters of weirs, but seldom from those of reservoirs on account of the great fluctuation of their water level. Well irrigation is a special form of this kind of irrigation. Lift irrigation sometimes supplements flow irrigation when the supply for the latter fails. The disadvantages of this form are the expense it entails on the cultivator and the possible dispersion of the irrigated area, entailing increased cost of supervision. The advantages of lift irrigation are the economy with which supply is used and the utilisation for cultivation of all water which is available.

In India water is usually lifted by the cultivators themselves by means of appliances which, although primitive, are, however, adapted to their requirements. Only one large Government pumping installation has as yet been there constructed; in Egypt irrigation companies have found it pay to pump water. When water is pumped it is more than ever necessary to prevent waste, as the value of the pumped supply is so high. Wherever practicable it is advisable to change lift into flow irrigation, as the latter is much preferred by the cultivators on account of its economy to them.

7. Flood Irrigation.

Flood irrigation consists in diverting river flood water on to lands which are above the ordinary level of supply and soaking them so thoroughly that crops can be grown on the flooded area. A few torrents in generally rainless areas are utilised in this way in India, but the cultivation thus rendered possible is of a precarious nature. In Egypt this form is known as "basin irrigation," the flood water of the Nile being poured into and temporarily stored in series of very large basins one below the other. These basins are surrounded by earthen banks of some size, and the supply to and from them is controlled by massive masonry inlets and escapes. Even there this form of irrigation is giving place to the more certain cultivation by canals led from barrages, or weirs, which raise the level of the river. An advantage of flood irrigation is that as it covers the land with a deposit of fertilising silt, artificial manures are not required nor are fallows necessary. For this reason some cultivators in Egypt prefer it to canal irrigation, as they think the latter is leading to a deterioration of the land.

8. Inundation Irrigation.

(*a*) *Description.*—Inundation irrigation is practised on the very large rivers of India that flow through the alluvial plains (which they themselves have created by the deposit of silt), and have a large but fluctuating discharge for several months in the rainy season, and thereafter a considerably smaller flow which gradually diminishes during the fair weather. The canals come into operation as the rivers rise above their beds, and cease to flow when the water level falls below those beds. The desiderata for a good season are that the first rise should be an early one, that the fair irrigating level should continue for some time, and that the last rise should be late and of some height.

Originally the canal heads were uncontrolled open channels leading from the rivers, but now, where practicable, brick-work head regulators, some of very large size, are built to shut out heavy floods, which, if admitted, might damage the canals and submerge the irrigated areas.

(*b*) *Disadvantages and Advantages.*—The great disadvantage of inundation irrigation is the fluctuating nature of the supply: the engineer is thus not responsible for the discharge of his canals beyond maintaining the works in good order, and making by careful and prompt regulation (often a matter of great difficulty) the most of the water available. The distributing works have to be much larger than those of permanent canals so as to utilise the maximum amount of flow practicable during the short time it is available—this naturally tends to make the irrigators lavish in the use of water during good seasons and clamorous for supply in bad ones.

A further great disadvantage of an inundation river which has not a fixed course is that changes in that course may lead to the destruction by erosion of the canal head and regulator, to the complete stoppage of supply by the river leaving the canal head dry, or to considerable diminution of discharge by the silting up of the canal head. A remedy for this when practicable is to link up a series of canals together (Art. 235) and to feed the set from a head which is not liable to be injured or left by the river. A still better remedy is to fix the river course at the head of the system by a massive weir built across it, and this also raises its level: inundation is thereby changed into flow irrigation. Inundation canals are particularly liable to heavy silting, which leads to large expenditure on their clearance, but by proper design (Arts. 204 (*d*) and 205 (*b*)) the amount of silt can be much reduced.

The advantages of inundation irrigation are that it makes available a large quantity of water at a cheap rate for the irrigation of large areas of alluvial land with convenient gentle slopes, which would otherwise practically be unculturable, and the water brings down with it fertilising silt. Moreover, as there is generally but little rain on such tracts the crops do not suffer from unseasonable downpours.

9. Well Irrigation.

(*a*) *General Remarks.*—Ordinary wells are usually excavated by the irrigators themselves, and each is generally utilised by a single man, although wells with a very large supply are sometimes owned and worked in common by several proprietors for their individual cultivations. In some countries artesian wells have been made use of for irrigation: their great cost may require capital raised by corporations or furnished by the State. In India the average cost of a permanent well varies from Rs. 300 (£20) to Rs. 600 (£40) according to the size and depth, and a very large one costs over Rs. 1,000 (£66). In the Punjab the average area irrigated by a well is 12 acres, elsewhere it varies from 2 to 4 acres. Although a single well irrigates a small area, the very large number of wells in some countries there makes this kind of irrigation a most important one.

Wells should be dug of a fairly large diameter so that they may collect and store subsoil water when they are not being drawn upon. They should be sunk in porous or fissured strata, and, when practicable, near a surface supply such as a river. The extent of underground catchment should be as large as possible; this will frequently depend upon the surface catchment which can be determined by inspection. In certain cases the supply of a well can be increased and made more permanent by boring in its bed so as to tap lower fissures, or by means of horizontal adits, both of which methods enlarge its catchment.

(*b*) *Disadvantages and Advantages.*—The principal disadvantage of wells is their cost both in construction and working. The latter has been estimated at not less than three times that of flow irrigation, but if the labour of men and animals is included, the excess cost must be considerably greater than this. Another disadvantage is that the water being practically pure has no fertilising properties in itself, and therefore the land requires the application of a good deal of manure, which involves an additional expenditure of labour and money. This disadvantage is to some extent shared by irrigation from reservoirs, as a considerable amount of fertilising silt originally suspended in them is eventually deposited on their beds, and is thus not led on to the fields.

The advantages of well irrigation are many. It is under the owner's sole control ; it allows isolated areas to be irrigated ; it utilises water which would otherwise be lost underground ; by lowering the subsoil water level it assists in the drainage of irrigated land which might become water-logged ; it is not likely to fail in seasons of drought, as then water is obtained in the wells from the rain which fell in previous years ; it permits of perennial and hot-weather crops being grown under canals, the supply of which fails in the fair weather ; it economises supply ; in the cold weather it furnishes water which is warmer than that from surface sources and is then preferred to that ; it is peculiarly adapted to intensive irrigation of valuable produce, and to the cultivation of two or three crops off the same area in a year.

Although the extension of well irrigation is not likely to be undertaken directly by the State, it can be effected indirectly at practically no cost to the public by a proper system of advances for construction to the cultivators.

(*c*) *Boreholes.*—Boreholes alone are sometimes made use of for irrigating small areas near homesteads, and for this purpose should usually not be less than 6 inches in diameter. As a rule, the water is lifted from them by means of windmills into small reservoirs, where it can be stored to tide over periods when the wind fails ; the cost of such water is probably at least double that stored in ordinary large reservoirs. In America it is reckoned that a plain windmill installation will serve for the irrigation of 3 acres, and that, when a reservoir is added, for from 5 to 15 acres. The disadvantages of windmills are that the wheel has to be thrown out of action when the force of the wind rises beyond a certain limit, so that increased pumping cannot then take place, and that they are liable to get out of order and require skilled labour for repairs.

10. Sub-Irrigation.

In this form of irrigation usually stoneware pipes with open joints, or special orifices, are laid under the entire cultivated area from 5 to 10 feet apart and from 2 to 3 feet below the surface; concrete, wooden, or iron pipes (under pressure) are sometimes used instead. The disadvantage of this system is that its expense is great, and it can therefore be adopted only for valuable produce, such as that of orchards. Unfortunately, in the case of fruit trees, the fibrous roots enter the pipes and block them, and no remedy for this has been discovered. Sub-irrigation is therefore rarely practised; it is most successful for edible roots such as beets, carrots, and potatoes, and is best suited to loam soils. Another objection is that by it the water tends to wet only the cold and sour subsoil, and does not sufficiently moisten the warm and rich surface soil; this explains why a smaller yield is usually obtained from sub-irrigation than from surface irrigation. The advantages of the system are that it effects great economy in water supply, as there is not practically any surface evaporation (since the moisture rises by capillarity in radiating lines from the orifices through the earth, but does not appear at the top); also, it does not cake the ground, and thus saves constant cultivation to preserve the tilth, but in regard to out-turn of crop the saving is not advantageous.

11. Navigation and Irrigation.

(*a*) *Combination inadvisable.*—In earlier days navigation was combined with irrigation on certain large canals in India, so that means might be afforded for conveying produce at a cheap rate. Experience has shown that the combination is not effective for the following reasons, and it is therefore not made in modern works. For irrigation a canal should serve the land to be cultivated; for navigation it should connect that land with the markets as directly as possible: it is seldom that one alignment will serve both purposes equally well. For irrigation a canal should have a constantly diminishing section and a fairly rapid flow to prevent silting and reduce cost, and a level fluctuating with the demand; for navigation it should have a uniform section and a velocity not exceeding 1½ feet per second, and should be maintained at a practically constant level. A boat moving upstream in a quick-flowing canal would cause waves, which would wash its banks, and might necessitate protection against their action. Certain works cannot serve both purposes, e.g. a fall on an irrigation canal requires a lock for navigation; other works are inadmissible for a combined scheme, e.g. siphons, superpassages, inlets and escapes, and low bridges, which are economical for irrigation, but cannot be constructed for navigation canals. For navigation canals overbridges have to be made extra high for the passage of boats and extra wide for the construction of the towpath; further, for them greater depth and width of waterway beyond the requirements of irrigation may be necessary.

(*b*) *Separate Systems advisable.*—The best arrangement is therefore to utilise navigation canals for boat traffic alone; the chief advantage of such canals is for heavy or bulky merchandise which need be transported only slowly and which cannot stand high freight charges. The canals are thus supplementary to railways and are useful to them, as they reduce rates only for not very remunerative traffic, and leave open to the latter the field for better paying goods. For this reason in many countries canals are considered to be public works, which may justifiably be financed by the State; even in England it is now proposed that Government should spend a very large sum in remodelling and extending the old inland navigation canals, which have practically fallen into disuse through railway competition and acquisition.

Objections raised to purely navigation canals are that their routes may be devious, the time occupied by traffic on them is considerable, cross communication or connections between different systems are difficult, and feeder canals, serving areas subsidiary to those tapped by the main canals, cannot be constructed as easily as feeder railways. Despite all this, there are cases where they furnish the cheapest and only practicable means of development, and each such case should be considered on its merits.

12. Cultivation.

(*a*) *General Remarks.*—Irrigation to be successful must be combined with careful cultivation, without which the application of water to soils will not produce the heaviest weight of crops. The crops to be grown should be selected with reference to the soils available, and to the seasons during which they are to be matured. Fertile soils will produce crops with a smaller quantity of water than will infertile ones; on the former heavy applications of water are also not likely to be so wasteful as they are on the latter. Well cultivated soils require the smallest amounts of water, as evaporation from them is at a minimum (Art. 17 (*c*)). Cultivation and irrigation long continued and properly conducted improve the quality of soils, but if improperly carried out, deteriorate it.

(*b*) *Regulation of Water Supply.*—Irrigation water which descends below the reach of the roots of the crop is not only wasted but is harmful in removing the soluble constituents of the soil and manure applied to it (but see Art. 24 (*b*)). When a great excess is used on retentive soils it will water-log them, and may cause salts to rise to the surface by capillary attraction, which may injure or destroy the crops. The water supplied should suffice only for the proper growth of the plants and to make good the loss by evaporation from them and the soil; this last loss is increased on bare soils when they are saturated, and generally in greater proportion than the excess of water applied. The less water with which a crop can be brought to maturity the greater the yield.

(*c*) *Reduction of Evaporation.*—In order to diminish loss by soil evaporation, the ground should be carefully hoed so as to form a dry "tilth," which prevents water rising to the surface by capillarity. Heavy waterings should therefore be succeeded as soon as possible by such loosening of the soil. In some parts of the United States and Australia, where the rainfall is scanty and the means of irrigation not available, "dry farming" is practised: this consists in keeping a good tilth continuously, whereby fair crops are grown with a minimum of moisture. This does not imply that irrigation is not desirable, as the application of it would increase the yield; moreover, the expense in labour of dry farming is much in excess of that where crops are irrigated. The formation of a good tilth is more effective on clay and sand soils than it is on loamy ones, but usually increases the yield on all kinds of soil by aerating them.

(*d*) *Manure.*—Irrigation by producing heavy crops greatly exhausts the land; it is an agricultural maxim that as much should be returned to the soil as is taken from it, and therefore to preserve its fertility undiminished it is necessary that enough manure should be cheaply procurable for this purpose. The availability of sufficient manure is thus an important point for consideration when a new irrigation scheme is under contemplation. Where the supply is from muddy sources the silt brought down may suffice for this, but where irrigation is carried out with clear water, artificial manures will have to be obtained or fallows allowed. Manure applied as a mulch lessens the amount of evaporation from land and thus reduces the quantity of irrigation water required by the crop.

(*e*) *Rotation of Crops.*—Different crops remove different constituents from the soil, so that, by growing them one after the other in rotation, the effect of a fallow is partly obtained for each crop; during the interval the land is resting from cultivation the constituents previously utilised are replaced by weather conditions acting on the soil. The lowest form of rotation in India is a quinquennial one, namely, one of perennial or hot weather, one of cold weather, one of eight months, and two of monsoon dry crops. The highest form of rotation there is a triennial one, which consists in growing only the three classes of crops first mentioned. As irrigation enables the most remunerative and highly-rated crops to be grown by intensive cultivation, it should, as far as possible, be limited to them. Cultivators naturally think they know their own interests best, and should not be bound to grow certain crops, but they can be induced to utilise irrigation most efficiently by providing them with an assured supply of water and by adjusting the rates for different crops so that they will of their own accord use that supply in the most profitable manner (Art. 26 (*a*)).

13. Reclamation of Alkaline Lands.

(*a*) *Effect of Over-Irrigation.*—Soils may be naturally alkaline, or may be made alkaline by bringing up by capillary action salts from the subsoil by over-irrigation or seepage from upper lands, or by conveying the salts on to the land by irrigation water containing them in solution. The first two of these actions of irrigation are generally much the more important, as it is but seldom that the freshly applied water is charged with salts to an injurious extent.

(*b*) *Alkaline Salts.*—The salts which most commonly render the soil so alkaline that it will not grow crops are the chloride, sulphate, and carbonate of soda : these are collectively known in different parts of India as ***usar, kalar, shora*** and ***reh***. In America the last named is called "black alkali," since soils charged with it have black puddles formed thereon by rain, etc. ; it is the most prejudicial of all, as it causes corrosion of the outside of plants near the ground surface, thus in fact ringing and destroying them, and often produces an impervious hard layer, or "hard pan," some depth below the surface. The two salts first mentioned when in combination make what is called "white alkali" ; the sulphate is the less harmful of the two. The insoluble carbonate of soda can be changed into the soluble sulphate by the application of gypsum (sulphate of lime), and can then more easily be dealt with. All three salts are due to the decomposition of soils containing the elements of which they are formed, and all can be removed by similar means. Alkaline soil is often also rich in other salts which are of a fertilising nature—such as sulphate of potash and phosphate and nitrate of soda—and any process of reclamation to be successful must get rid of the deleterious salts and preserve the beneficial ones for utilisation by the crops.

(*c*) *Methods of Reclamation.*—If the natural subsoil and surface drainage can pass off the hurtful salts as rapidly as they are formed, the land will not deteriorate. If, however, that drainage is not sufficient for this (which is the case in alkaline soils, as these are generally impermeable), the excess of salts will be carried upwards to the surface by capillarity, and will there be concentrated by evaporation. The rise of the subsoil waterplane must thus be watched carefully, as it gives warning that water-logging and probable deterioration by salt efflorescence will occur unless the water supply on the area irrigated is reduced.

When damage has occurred, the remedies to be applied are therefore to limit the saturation of the soil and to diminish the evaporation from it. The former can be effected by restricting the amount of irrigation water and by draining the soil by a series of deep drains. Evaporation can be lessened by growing a crop so as to form a dense shady cover, and especially a deep-rooted one, such as lucerne, which draws its moisture from the subsoil, and not from the surface (see

Art. 17 (*d*)). Egyptian clover (berseem) is also a good crop for this purpose. Deep ploughing, by diluting the upper crust with the lower less-charged soil, or for the same reason, adding sweet soil to the fields, or scraping off the salt efflorescence from them, have a good, but temporary, effect, as the salts again rise to the surface. Leaching the ground by flooding it to a depth of a few inches and then draining off the water rapidly after a few days is recommended by some, but others hold this will carry much of the salt into the subsoil, whence it will again rise. Repeated applications of the process must, however, remove the deleterious salts, but they will also carry off the beneficial ones. Silty water, which brings fresh sweet soil on to the fields, is the best to use for flooding. In the Punjab it has been found efficacious first to enclose the lands (so as to prevent the entry of cattle, which destroy young shoots), in order to encourage the growth of coarse natural grass, which, when protected, can flourish in such soils, and by assimilating the salts, will remove them. Thereafter the area is liberally dressed with manure for one or two years and well ploughed, after which rice, and subsequently other crops, can be grown on it. The preservation of a good tilth by ploughing after each watering, mulching, manuring, and the covering of the land by vegetation, are effectual remedies, especially when combined with deep drainage.

(*d*) *Economic Effect of Reclamation.*—The expense of reclamation is likely to be heavy; although it may be less than that of irrigation by pumping on to high lands, as less water has to be dealt with, the crops produced on low-lying, salt-charged lands are generally inferior. The cost is justified only when there is a necessity for increasing the area to be cultivated or when beneficial salts are present in the soil.

14. Percolation.

Percolation or leakage (*vide* definition in Art. 2 (xiii)) may take place below storage reservoir dams, at cross-drainage works, and along porous parts of canals. If it passes naturally into the drainage lines of the country, it will not injure neighbouring lands; but should it not do so, it will tend to water-log these and be harmful. As it is practically impossible after the construction of a reservoir to make it more water-tight, great care should be taken when forming it to ensure its staunchness. The soddening of the base of an earthen dam may, moreover, cause the embankment to slip, and should be prevented by drainage. Percolation from newly-excavated canals often decreases as they become waterproofed by the deposition of silt originally suspended in the water. When this does not occur, defective places should be made good by means of puddle trenches, lining the canal, or waterproofing it (Art. 139 (*c*)).

15. Seepage.

Seepage, or subsoil flow (*vide* definition in Art. 2 (xiv)), may take place from reservoir basins, and from canals where the soil is permeable. If it passes deeply under ground to the drainage lines of the country it does no harm, but if its passage is hindered by impermeable strata downstream it will cause water-logging upstream: the remedy for this is deep drainage along or through the obstructing barriers, when that is practicable. Although the loss by seepage may be very considerable, it cannot usually be diminished artificially, as it takes place over large areas or long lengths and is deep-seated; care should therefore be taken when constructing reservoirs and canals to avoid porous country. In North Colorado it has been ascertained that the seepage returned to the rivers is one-third of the water supplied for irrigation; much of the cold-weather flow of the Indus in Sind is due to the previous monsoon irrigation, which takes place in the Punjab upstream, and increases with it. Seepage from irrigated lands is said gradually to diminish, probably because the subsoil pores become choked by the inflow of soluble material.

Seepage water is clear, and does not carry fertilising silt. Having filtered through a large area of soil, much of which may have been cultivated, it may have some manurial elements in solution; if, however, it is derived from alkaline lands, it is likely to be charged with injurious salts. Before it is proposed to irrigate with it, it should therefore be analysed.

The best way to utilise seepage water is by means of diversion weirs with canals led from them. It has been calculated that on the Pánjhrá river, in Khándesh, Bombay Presidency, the combined hot-weather flow of a series of seven such canals is double the discharge admitted from a reservoir into the dry river bed at the head of the system.

16. Drainage.

(*a*) *Construction of System.*—In the two preceding Articles the necessity for drainage in certain conditions has been explained. If subsoil water rises to or near ground level in alkaline soil, it will carry salts to the surface, and in sweet soil will water-log and sour the land by depriving it of aeration ; thus in both cases it will harm the crops grown. Stagnant water is insanitary, especially in tropical countries, as there mosquitoes breed in it and disseminate malaria ; even the rise of subsoil water is prejudicial to health. Instances of such bad effects have occurred so frequently on canal systems that many engineers recommend drainage should be arranged for from the start of irrigation works. However, the amount of water to be got rid of cannot well be estimated beforehand, as it depends, not only on subsoil and surface conditions, but also on the regulation of irrigation. The better plan would therefore seem to be to lay out the lines of future drains and reserve sufficient land for them from the first, but not to excavate the channels until the necessity for them has been established by the observed rise of the subsoil water. Thereafter, the drains should be dug and extended in length and increased in section as may be found desirable ; as a rule, they will have to be aligned in the lowest-lying ground of the irrigated area, and generally will follow valleys.

It must be remembered that the branch drains which deal independently with individual small areas will have a more or less intermittent flow corresponding to the actual irrigation of those areas, while the main arterial drains will have a nearly steady flow which is practically equal to the total average discharge of the former ; the effect of rainfall must also be considered and provided for. In Egypt, a rainless country, the estimated discharge is one-half and one-third of the irrigation supply for branch and main drains respectively. As that discharge involves so much waste of water and of the salts dissolved therein, it is necessary to diminish it, as far as this can be done, by careful regulation of the water poured on to the fields, for irrigators are naturally inclined to use that lavishly.

A good idea of how the country will stand the application of irrigation can be formed by noticing what is the effect of heavy rainfall on it. Where the surface has good slopes, is intersected by numerous well-defined natural drainage lines, and is of a porous nature, artificial drainage will probably not be required; where, however, the land is flat, even, and impervious, that will most likely be necessary. Unfortunately, drainage works are expensive to construct and maintain, and, where the conditions are adverse, the cost of a perfect system cannot be borne by an irrigation scheme. Money will there be most advantageously expended in keeping unobstructed the natural drainage lines, and particularly their outfalls.

(*b*) *Construction of Drains.*—Drainage water being clear, sunlight penetrates it, and thus weeds are apt to grow luxuriantly in it and to obstruct the flow. Drains should therefore be deep, so that they may be shaded even when they are running full; moreover, to prevent water-logging and the rise of subsoil salts their full supply should be kept at least 2 feet below the surface. The section of the drains should be carefully maintained, and especially the outfall should not be allowed to be blocked even during high floods, as then the drainage flow may be at a maximum. Where practicable, that should discharge into a natural drainage channel, but where this cannot be done, pumping will be necessary. On the seaboard drains should preferably discharge into the sea above high tide, rather than into a river, so as to secure the lowest outfall possible.

Drains below dams should also be deep so as to tap the low-seated subsoil water. It is best to fill in these drains with rocky *débris* from the excavations of the works, and to place the large particles at the base, to surround all with a 12-inch layer of fine particles to prevent the ingress of earthy matter, and to finish off the filling at the top by a 2 feet cover of soil carried a little above ground level. Such drains will continue to run clear, as their sides cannot fall in, surface silt cannot be brought into them, and weeds cannot grow in them.

17. Loss by Evaporation.

(*a*) *Evaporation from Water.*—Evaporation from the surface of water depends upon—

(i) The dryness of the air; i.e. is proportional to the difference of the pressures of vapour at the temperature of the water and at that of the dew point.

(ii) The temperature of the water; an increase of this leads to greater evaporation; thus shallow water which gets more heated than deep water evaporates more freely.

(iii) The movement of the air, as a still atmosphere obstructs the free diffusion of vapour—a strong, dry, hot wind is the greatest factor in causing evaporation.

The annual amount of evaporation in irrigating countries has been said not to differ greatly (presumably at any one place), and to vary from about 4 to 6 feet in depth at different places; this, if a correct statement, must be due to the different factors enumerated above, equalising each other on the whole, as climatic and replenishment conditions are not constant. Probably the statement is not correct, as it is well known evaporation at any one place varies considerably during the different seasons, and its annual amount depends therefore on the character of those seasons and the amount of storage in different years.

(*b*) *Measurement of Evaporation.*—Evaporation is generally measured in a small, shallow, open cistern, which exaggerates the effects of the temperature, by, it is said, as much as 50 per cent. To prevent this it has been recommended that for a reservoir a large deep cistern should be used, and should be immersed in a considerable body of water; even then the sides, which have to be higher than the external water surface so as to shut out waves, increase the temperature of the interior, but also protect that from the drying action of the wind. Possibly, by regulating the conducting nature of the sides, the two sources of error may be made to counterbalance so as to give a true result. In India the loss from evaporation in the hot weather may be as high as one-third of an inch daily; this shows how great is the annual loss on this account, and the necessity for utilising stored water as soon as possible in order to diminish that loss. When experiments are made it is essential that observations of all the factors influencing evaporation should be carefully noted and recorded. On the Ganges Canal the evaporation 52 miles from the headworks was found to be about 50 per cent. greater than at 34 miles upstream, owing to the canal water in its flow having become heated by the sun.

(*c*) *Evaporation from the Ground.*—Evaporation also takes place from moist bare ground, but lessens as the surface cakes and becomes impervious, so that its amount depends a good deal on the porosity of the soil, enabling subsoil water to be drawn up by capillary attraction to replace the original surface saturation, and, like it, to be evaporated subsequently. Anything which retards capillarity thus lessens the amount of evaporation, and hence the utility of preserving a fine tilth on cultivated land (Art. 12 (*c*)). Percolation through ordinary soil has been found to be only one-third that through sand, whereas evaporation from the surface of the former was four times that from the latter. Evaporation is increased by the over-saturation of the soil. The effect of evaporation is to reduce canal flow slightly, but the total amount of seepage from irrigated lands greatly (Art. 18 (*b*)).

(*d*) *Evaporation from Vegetation.*—Growing crops increase the total amount of evaporation beyond what would take place from the bare ground, although the plants by shading the land lower its temperature. This increase is due, partly, to the roots getting a greater supply of water from the subsoil (Art. 13 (*c*)), and partly, to the increased surface exposed by the leaves. Experiments in Germany have shown that meadow grass, a most exhausting crop in this respect, causes in summer a loss by evaporation of over a quarter of an inch a day, i.e. one nearly equal to that from a reservoir surface in the Indian hot weather. Evaporation from swamps in which aquatic plants grow is thus excessive.

18. Loss by Absorption.

(*a*) *Loss Considered.*—By the definition given in Article 2 (xvii) the loss by absorption considered is limited to that which occurs on the irrigation works themselves, but a similar loss occurs also on the irrigated area. In estimating the efficiency of the works, the latter loss is not directly taken into account, as it is included in the quantity of water reckoned as utilised for irrigations.

(*b*) *Causes of Loss.*—In a reservoir the loss by absorption depends upon the nature of the subsoils of the basin and the pressure head of the stored water on them; deep reservoirs and those having porous basins thus lose most from this cause.

In canals it has been ascertained that the loss—

(i) is greater in cuttings than in embankments;
(ii) varies directly as the wetted perimeter and depth of the channel;
(iii) depends upon the nature of the soils passed through;
(iv) decreases as the time of saturation increases.

The explanation of (i) is that cuttings may disclose leakage planes, and are generally more porous than embankments which are made of soil that becomes compact by settlement, even if it was not originally consolidated. Moreover, cuttings are in continuous contact with a large extent of subsoil, whereas in embankments the absorbent material is limited. A well-made bank thus early attains full saturation, and further seepage is not induced by the capillarity of downstream material and only slightly by evaporation from the exposed surfaces of the bank.[1]

The explanation of (ii) is that the extent of wetted perimeter determines the amount of filtering area, and the depth of the flow, the pressure head on it. A general allowance of 8 cusecs per million square feet of wetted perimeter is made in the Punjab, where the soil is fine-grained alluvium.

The effect of (iii) is obvious, as the rate of filtration depends upon the closeness of the grains of the filtering material, and its truth is proved by the well-known fact that as the bed and sides of canals get coated with silt they become more water-tight.

The reason for (iv) is that the resistance to filtration increases with the length through which the water has to pass. The water rapidly saturates the nearer parts of the soil, but, owing to increased frictional resistance to flow, is not able to pass so quickly through the more distant parts. Thus channels running with a constant depth lose relatively less water than those with an intermittent discharge; when the latter are out of flow, the previous seepage passes away downstream, and the wetting of the bed and sides is evaporated, thus rendering all more absorbent when again wetted. This is one reason why the loss is so heavy in field watercourses which are in operation at long intervals, although their generally inferior state of maintenance also greatly contributes to the waste by them.

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[1] A fountain pen laid on its side with the nib free will not lose ink, but, if the nib touches blotting paper, ink will be drawn off by capillarity.

An inference which may be made from (i) and (iii) is that the amount of underground seepage water returned to the river is chiefly due to the canal system, and not to the irrigated area (see also Art. 19 (*a*)). The bulk of the saturation of the latter can penetrate only to a shallow depth; comparatively little can descend deep, and the portion near the surface is subsequently dissipated by evaporation; against this may be said that the area wetted by irrigation is much more than that done by the canal system. The water absorbed from the canal generally starts more deeply seated, is continuously fed by the flow, and is diminished only slightly by evaporation.

Another factor which affects the loss by absorption is the height of the "water table," or natural top level of the subsoil saturation of the country. The higher this is below the bed of the canal, the shorter will be the course and the greater the rate of flow of the absorbed water to it; the total amount of seepage will, however, be diminished by the decreased extent of filtering area. When, moreover, the water table is above the canal surface, water will be passed by seepage into the canal, which will then act as a drain. Thus the loss by absorption tends to diminish with the rise of the water table.

(*c*) *Estimation of Loss.*—The following formula has been devised so that the loss may be approximately estimated—

$$\text{Loss} = \text{AL}^x$$

where A is the loss ascertained in the first mile;
L is the length in miles considered of the canal; and
x, the power to which L is raised: this varies from $\frac{5}{6}$ to $\frac{6}{7}$.

This formula can have only limited application, as it does not take into account the variations of (ii) and (iii).

It is desirable that the rate of loss by absorption of a canal should be determined by actual observation, so that its normal amount may be fairly well known, and so that especially defective parts may be discovered with a view to staunching them, if such remedy is financially practicable. In order that the experiment may be properly carried out, gauging stations should be formed at every mile or so, and observations should be made at them as nearly simultaneously as possible. For two or three days beforehand the canal, or the length under examination, should be maintained at constant and fairly high level and discharge by closing all outlets (this can be done either during a time of general closure or by arrangement with the irrigators), so that its wetted perimeter may attain its permanent rate of seepage.

19. Loss in Transit.

(*a*) *The Amount of Loss.*—The diminution sustained by the flow of water from the source of supply is known as loss in transit. All experimenters agree that in canals this is very great, although naturally the figures for it given by them vary somewhat according to the conditions under which they made their observations. It may be said that the loss is due to the following causes of waste:

(i) Absorption and evaporation in passing from the head of the canal to that of the distributary (20 per cent.);
(ii) The same from the distributary head to the irrigation outlet (6 per cent.);
(iii) The same while the water flows in the field channel (21 per cent.);
(iv) Wastage at the outlets and irregular distribution of water on to the fields, whereby some parts are over-saturated and others are left insufficiently irrigated (25 per cent.).

The figures given in brackets are the percentage losses which were ascertained on the Bari Doab Canal in the Punjab, and show that the balance quantity of water usefully applied to the land is only 28 per cent. of that supplied at the head of the canal.

The reduction of the loss of 26 per cent. on the canal and distributaries is directly in the power of the canal officer to effect as far as practicable, but he can only indirectly diminish the greater loss of 46 per cent., which occurs after the water has passed through the irrigation outlets, by inducing the irrigators to practise economy, and, if necessary, by imposing penalties for waste. It is of great importance that the loss should be reduced, as thus it will be possible to increase the irrigation area under the canal.

(*b*) *Allowance for Loss.*—The loss in transit under (i) and (ii) is so considerable that it should be allowed for when calculating the discharging capacity of a canal and its branches and distributaries. If there is a neighbouring system with similar physical conditions, the results obtained on it should be taken as guides. If, however, the canal is to be in a country hitherto unirrigated, estimated allowances for loss will have to be adopted. The following are given as rough general approximations of the loss per mile when the soil passed through is of a fairly retentive nature :—

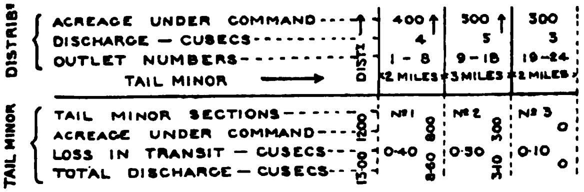
Discharge 100 cusecs and over	..	0·25	per cent	(0·98)
,, from 50 to 100 cusecs	..	0·50	,,	(2·67)
,, from 25 to 50 cusecs	..	1·00	,,	(5·22)
,, from 10 to 25 cusecs	..	2·00	,,	(7·48)
,, 10 cusecs and under	..	3·00	,,	(—)

For impermeable soils smaller allowances should be made, and for permeable soils greater ones. In numerous experiments[1] made in California the losses determined were from four to five times those proposed above, and are entered in brackets alongside them. This shows the desirability when practicable, of aligning a canal so as to make it pass through highly retentive soils.

(*c*) *Calculation of Loss.*—The calculations will have to be made commencing with the tail section of the tail minor, and working upstream to the head section of the main canal. The discharge of the supplying channel above and below the take-off of each group of outlets on the minors, and each distributary or branch canal will have to be ascertained in some such way as shown in the diagram and tables below :

FIG. 1

DIAGRAM OF DISCHARGES



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[1] U.S. Department of Agriculture, 1902, p. 31, of *Bulletin*, W., by Elwood Mead.

Tail Minor.						Discharge in Cusecs.				
Section Number.	Numbers of Outlets in Section.	Area under Command in Acres.			Length of Section in Miles.	Utilised by Section (Duty—100 Acres per Cusec).	Loss in Transit in Section.	Total (Column 7 + Column 8).	Of Section.	
		Of Section.	Below Section (*vide* Column 3).	Total (Column 3 + Column 4).					At Tail.	At Head. Col. 9 + Col. 10.
1	2	3	4	5	6	7	8	9	10	11
3	24–19	300	—	300	2	3·00	0·10	3·10	—	3·10
2	18–9	500	300	800	3	5·00	0·50	5·50	3·10	8·60
1	8–1	400	800	1200	2	4·00	0·40	4·40	8·60	13·00

The entries in column 8 above are thus calculated :—

Section Number.	Discharge of Section in Cusecs.					Percentage Loss in Transit per Mile.	Length of Section in Miles.	Calculated Loss in Transit in Cusecs. Col. 6 × $\frac{\text{Col. 7}}{100}$ × Col. 8.
	At Tail.	Utilised in Section.	Approximate Loss in Transit.	Approximate at Head (Col. 2 + Col. 3 + Col. 4).	Approximate Average ½ (Col. 2 + Col. 5).			
1	2	3	4	5	6	7	8	9
3	—	3·00	0·10	3·10	1·55	3	2	0·09, say, 0·10
2	3·10	5·00	0·50	8·60	5·85	3	3	0·53, say, 0·50
1	8·60	4·00	0·40	13·00	10·80	2	2	0·43, say, 0·40

The entries in column 4 of the second table are arrived at by first calculating those in column 9 without taking column 4 into account. Or, the calculations can be made by estimating the loss per million square feet of wetted perimeter of the channels. In this case the discharge and section of the channels will first have to be determined approximately before, and then corrected after the loss in transit is included; the labour involved can be reduced by using tables of discharges and sections.

(*d*) *Loss down Natural Channels.*—Water is sometimes passed from a reservoir down a stream bed to the intake weir at the head of a canal system. It is difficult to estimate what will be the loss in transit down the stream, but it will similarly be due to evaporation and absorption. It will thus be at a maximum when the stream is tortuous and its bed broad, sandy, and naturally dry, and at a minimum when that has a direct course and the bed has a defined, narrow central trough, consists of dense unfissured rock, and is charged with subsoil drainage water. To enable the estimate of loss in transit to be prepared, observations should be made of that which takes place when the stream is in natural flow corresponding in amount to what its discharge will be when the stored water is passed down it; an allowance should be made for the effect of natural seepage in the former case in reducing the observed loss.

20. Lining Canals.

In order to reduce loss in transit certain canals have been lined with impervious material, and it has been proposed to line others. As the process is expensive, it must first be determined if the capitalised value of the water likely thus to be saved is greater than the cost involved. The lining adopted should be cheap, durable, easily available and maintainable, and should not be liable to damage by cattle trespassing on it. If a smooth, hard lining is formed when the canal is originally made, there will be some saving over the cost of applying it afterwards, as in the first case a higher velocity can be taken into account and the canal made with a better discharging section than is practicable with an unlined channel; thus the amount of lining can correspondingly be reduced. Generally, however, as the full extent of irrigation is not likely to take place at first, it is better to defer the great expense of lining until its necessity has established itself. During this period the canal may become more water-tight by the deposit of silt on its bed and sides, especially if muddy water is passed down it. Lining will often be justifiable financially for waterproofing exceptionally leaky parts, and especially watercourses in sandy soil, as there the loss of water is at a maximum. The permissible cost per mile on certain Indian canals has been calculated to be, for discharges—

2 to 10 cusecs	..	from Rs. 2,000 to Rs. 10,000
20 to 100 cusecs	..	from Rs. 3,000 to Rs. 11,000
500 to 1,000 cusecs	..	from Rs. 6,000 to Rs. 27,000

after taking into consideration the probable proportionate time the channels will be flowing.

In the Punjab experiments were made with linings (Figs. 2 and 3) of pure Burmese crude petroleum oil, coal tar, lime and cement, mortar slurries, clay slurry, earth and clay puddles, and neat cement; of these the oil was found to be easiest applied and much the most efficient and economical, while clay puddle was the worst. On account of the capillarity of pervious soil it would seem better to continue the linings to ground level, or to 2 feet above full-supply level, whichever is less, than to stop it lower as shown in the figures. The experiments had, however, not been continued long enough to establish the permanency of the results obtained nor the best depth for the earth cover. In California channels have been excavated to a high discharging section and lined by means of a special machine, with concrete cement-plastered. Sub-irrigation (Art. 10) may be considered to be the ultimate form of lining for watercourses.'

FIG. 2

OIL, CEMENT, LIME & TAR LININGS

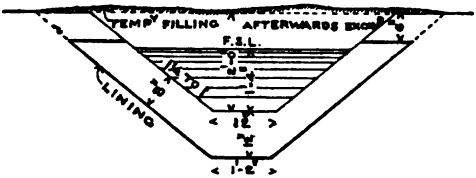
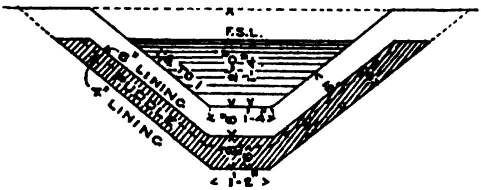


FIG. 3

PUDDLE LINING



When the water supply is abundant, it will generally be found a cheaper and more permanent arrangement to widen the canal, and thus to increase its discharge, than to line it. Also, where the loss of water by seepage from an upper work is utilised by a lower one, it may not be advisable to go to great cost in making the former staunch. Where, however, water is scarce and is also valuable on account of the class of crops irrigated thereby, lining may often prove desirable and remunerative.

21. "Duty" of Water.

(*a*) *Various Descriptions of Duty.*—The duty of water is a term used to indicate the irrigating capacity of water as estimated beforehand or as determined by actual results. It is stated either according to the rate of flow of a canal or to the total quantity of water expended.

The flow duty of a canal does not by itself indicate the total quantity of water used in irrigating the crops: in order that this may be arrived at, must also be known the "base" of the duty, which is the time during which the crops are under irrigation. This class of duty is variously expressed thus:

(i) In India, by the number of acres irrigated by the constant flow of a cusec (1 cubic foot a second).
(ii) In America, by the similar number irrigated by a "second-foot" (1 cubic foot a second), or by a "miner's inch" (which varies in different parts from $\frac{1}{40}$ to $\frac{1}{50}$ of a second-foot).
(iii) In Egypt, by the number of cubic metres (35·31 cubic feet) used for each *feddan* (about 1 acre) in twenty-four hours.
(iv) In Southern Europe, by so many litres (0·0353 cubic foot)—or sometimes cubic metres—per second per hectare (2·47 acres).

The quantity duty of an irrigation work is thus stated:

(v) In India, by the number of acres irrigated by the storage of a million cubic feet.
(vi) On the large canals of Northern India, by Δ, or "delta," the average depth in feet poured on to the land.
(vii) In America, by the number of "acre feet" expended per acre irrigated (an "acre foot"

is the quantity of water required to cover an acre 1 foot deep, i.e. is equal to 43,560 cubic feet).

The relation between these three duties is simple—

$$\frac{1{,}000{,}000 \text{ cubic feet}}{\text{acres} \times 43{,}560 \text{ square feet}} \left(\text{say } \frac{23 \text{ feet}}{\text{acres}}\right) = \Delta \text{ in feet} = \text{acre feet.}$$

(*b*) *Factors affecting Duty.*—The duty varies in accordance with the following factors:

(i) Method of cultivation (including tillage and irrigation)—this is the most important element and is most susceptible of improvement as the skill and care of the irrigators increase.

(ii) Nature of soil—through which the canal flows and of the irrigated area—including its constitution (permeable or impermeable), its surface slopes, and the spring level of the ground; these affect the loss by absorption.

(iii) Climatic conditions—temperature and dryness of the air and the force of the wind (affecting the loss by evaporation) and the rainfall.

(iv) Canal conditions—rapid flow, increasing the duty, or slow flow diminishing it; concentration, or dispersion, of the irrigated areas with regard to the source of supply (which respectively act similarly); the amount of fertilising matter in the water; the methods of applying the supply (Arts. 23 (*b*) and 24 (*a*)); and the system of payment for supply by quantity consumed or area irrigated.

(v) Species of crops grown (Art. 24 (*b*)).

The amount of rainfall is popularly supposed to be the principal factor determining the amount of artificial watering required. This, however, is not strictly true, for there are cases where the duty is low although the rainfall is high: the explanation probably lies in the suitability, or otherwise, of the rainfall to the requirements of the crops, and it is likely the discrepancy would disappear if only the useful falls were taken into account (Art. 48 (*c*)).

(*c*) *Utility of Observations for and General Allowances for*

Duty.—These factors affect the duty so greatly that it varies on every work and often on different parts of, and at different times on, the same work, so that it cannot well be predicted. The utility of ascertaining the duty on existing works is that it enables a comparison to be made of the efficiency of their management in different years, and forms a guide for designing proposed works, for which purpose an intimate acquaintance with the conditions that obtain is necessary. As a rough indication it may be said that during very hot weather in the tropics a duty per cusec of 60 acres, in less hot weather there one of 100 acres, and in temperate climates one of 150 acres should at least be obtained in ordinary conditions at the head of a canal, and ones of 4, 6 and 8 acres, respectively, per million cubic feet stored in reservoirs in such climates.

(*d*) *Variation due to Place of Observation.*—The duty depends upon where the observations are made; owing to the loss in transit it is smallest when calculated at the source of supply and greatest when estimated at the irrigated area. Duty is generally reckoned on the total quantity supplied at the head of the system and also on that " utilised," i.e., after deducting therefrom water passed out at escapes or which does not flow to the irrigated area concerned. It is desirable to ascertain the duty at different parts of the system in order to detect where wastage occurs, so that that may be reduced, and at different seasons so that the maximum efficiency then possible may be determined.

The estimation of the duty of a proposed canal is necessary in order to ascertain its discharging capacity and section. To provide for times of pressure when water is most needed the worst conditions for irrigation should be taken into account. The ascertainment of the duty at the head of a system is required so as to arrive at the total quantity of water which should be provided.

(*e*) *Inundation Canals.*—For an inundation canal with a greatly fluctuating flow three kinds of duty may be considered, namely, those due to—

(i) The designed full-supply discharge, for obtaining data for designing new canals.
(ii) The average discharge, for comparing the working of the same canal in different years.
(iii) The minimum discharge, for ascertaining the

highest duty possible, as the canal with this has to maintain the largest area of irrigation practicable.

(*f*) *Regulation of Duty.*—On a new work it is best to start with comparatively low duties, as then there will be ample water available for the small acreage likely at first to be irrigated. The irrigators should, however, clearly be given to understand that power is reserved to increase the duty, and thereby the acreage. The continuous growth of the irrigated area is an important feature of a successful work.

22. Economy of Water.

(i) Stored water should be utilised as soon as practicable in order to reduce to the minimum the loss by evaporation and absorption in the reservoir. When a reservoir usually fills and runs to waste, irrigation during the rainy season should be encouraged so as to take advantage of the surplus supply then. For this purpose high-level channels may be taken out a little below reservoir full-supply level, so as to secure additional command near the source of supply.

(ii) To economise water the alignment of all channels should be as direct as possible, so that the course to the fields should be the shortest practicable.

(iii) The velocity of flow should generally be the greatest which the soils can stand so as to reduce to the minimum the section and thus the capital cost of the works.

(iv) Water should be led down defined channels; it should not be allowed to spread over waste land, nor to flow down wide natural channels, nor from one field or plot to another; otherwise, the loss in transit will be great.

(v) Porous and sandy soils and fissured rock should be avoided in canal alignments, but when this is not possible, excessive leakage should be prevented by puddle trenches or other staunching arrangements (Art. 20).

(vi) Water should be allowed to flow in rotation in the different sections of the canal system with the greatest discharge and for the shortest period practicable, so as to diminish loss by absorption.

(vii) The depth of individual waterings and the intervals between them should be regulated so as to secure the proper irrigation of crops with the minimum amount of water and smallest loss by evaporation and absorption (Art. 24 (*b*) and (*c*)).

(viii) As much leakage occurs at outlets (Art. 231 (*b*) and (*c*)), their number should be reduced as far as possible, and as much loss in transit occurs down field channels, they should be maintained in good order (Art. 231 (*a*)).

(ix) To lessen loss in transit, the irrigated area should be concentrated and be as near the source of supply as practicable.

(x) Irrigation during night-time is wasteful because it cannot easily be supervised, otherwise it would be economical of supply, as loss by evaporation from the irrigated area would thereby be diminished. During the night the flow should be passed to the lower part of the system or into tail reservoirs (Art. 143).

(xi) The assessment of irrigation water by measurement of the quantity supplied and not of the area irrigated has been strongly advocated as much the more economical system of the two (Art. 45).

(xii) Careful supervision of irrigation is the best means of preventing waste and economising supply.

23. Distribution of Water.

(*a*) *General Remarks.*—Water may be considered to be the finished product of irrigation works, and therefore its proper distribution requires the most careful attention in order to secure the best results. Economy in construction and the natural advantages of good sites will not bear their full fruit if, after all, the distribution of water is carried out inefficiently and lavishly. An economical distribution of water makes the supply go further, thus increasing the area irrigable, the revenue from it, and the benefit to the country. It will tend to prevent water-logging of the ground by the rise of subsoil water, and the leaching of plant food from the soil, may obviate the necessity for drainage works, and may lessen the silting of the channels. The control of the irrigation supply becomes an absolute necessity during periods of deficient discharge, and that it may then be most effective, the irrigators should be accustomed to it at all times, and thus learn how it secures impartial and fair distribution to them.

(*b*) *Rotation of Supply.*—The best way to economise supply is to pass the water in regular rotation to the fields. At first in Upper India it was the practice to let all the channels flow continuously, and to close the different outlets on them for stated periods. The outlets being very numerous, it was not practicable for the superior staff to supervise their working, and thus administrative abuses occurred. Moreover, when the supply fluctuated, the main branches could not work in accordance with their design for full-supply ; also, as they were in constant flow, they lost much water by seepage (Art. 18 (*b*) (iv)), and tended to raise the subsoil water level and cause salt efflorescence on the land.

The more modern practice is to work in rotation the minors supplying the field channels, and in seasons of scarcity the distributaries or branch canals alternately. This secures the following advantages :

(i) Proper administrative control over distribution by superior authority, and with a reduced canal staff.

(ii) The maintenance of the proper régime of the channels by running them full, or nearly so, during the period of flow, thus letting them maintain their designed velocity and thus reducing silting.

(iii) Reduction of seepage and evaporation while the channels are dry. (Although a channel flowing intermittently loses more water while in operation than does one with a steady discharge (Art. 18 (*b*) (iv)), in the intervals when it is dry there is no loss from it, and thus on the whole the total loss from the intermittent is considerably less than that from the constant channel.)

(iv) The convenience of the irrigators by rendering interference with the working of their outlets unneccessary, as all are entitled to flow full while water is being passed down.

(v) The reduction of the loss by leakage at numerous outlets supposed to be closed, but in practice not actually water-tight, and of waste at the tails of many minors in constant small flow.

(vi) The prevention of the unauthorised use of water at outlets not entitled to supply during the rotation.

(vii) The fair distribution to all irrigators from the head to the tail of their minor.

To ensure the proper working of a system of rotation time-tables should be prepared showing when the various channels or sections of them and the outlets from these will be in flow and when closed. These tables will have to be devised so that the crops may get waterings at the required intervals, and so that the minimum length of channels practicable will be in flow at the same time. Such regulation necessitates a large amount of gauging, the results of which should be promptly and regularly communicated to the controlling authority.

(*c*) *Non-rotation Irrigation.*—It is the tendency of irrigators to take as much water as they can, and thus the upper men often appropriate more than their fair share. To prevent this, when there is not a proper system of rotation, the supply should be given to the lowest irrigator first, and then cut off and allotted to his upstream neighbour, and so on. By this means a dribbling discharge running to waste at the tail of the channel will be prevented. Similarly, the more downstream distributaries should flow first.

24. Waterings.

(*a*) *Subdivision of the Irrigated Area.*—The watering of a field is usually commenced from the top, and should be stopped as soon as the lowest part has received sufficient supply. All the time thus taken the upper parts are absorbing water and getting an excess supply. To secure more uniform watering, it is obvious that the whole field should be divided into small plots to be separately irrigated, and this can be done by forming small ridge banks about 12 inches high to enclose the individual plots. The size of these plots should vary directly with the flatness of the ground, the nature of the soil and the rate of discharge, which factors affect the uniform distribution and the rate of travel of the irrigating water. The more level the land, the more retentive the soil, and the greater the discharge, the larger may be the compartments. In the Punjab, where the land is level and moderately porous, 110 feet by 55 feet has been found a convenient size, but 70 feet by 70 feet has been recommended, and also a square shape, to equalise the watering better. For good loam the time taken to cover each plot should not exceed two hours, and for sandy soil half an hour. To reduce the plots still further in size would lead to still greater economy of supply, but would press unduly on the cultivators. Each of these plots should be supplied direct by an opening at its head from the watercourse, and on no account should water be allowed to flow from one plot to another, as thus the whole economy of distribution intended to be secured by the subdivision would be lost. Further, to reduce waste, all large clods should be broken up, all depressions filled, and the surface generally made smooth and level.

As the expense of the preparation of the land into numerous levelled plots is considerable, another system of irrigation consists of small field channels running on gently falling contours, having a longitudinal slope of from 1 to 8 inches per 100 feet, with still smaller laterals at intervals by which the water is poured on to the ground. The laterals should be short, so that they may deliver their supply in the time which would be taken to cover the corresponding plots, and the field channels should be spaced apart accordingly. As in the case of the plots, the upper parts of the laterals receive more supply than the lower parts. In orchard cultivation comparatively deep furrows are led between the lines of trees, so that the water gets quicker to the roots and does not overflow the surface, which thus does not get caked when it dries—a result which follows surface irrigation; moreover, the roots are thus encouraged to descend into the soil and not to rise to the surface.

(*b*) *Depth of Watering.*—The disadvantages attending too profuse irrigation are mentioned in Article 12 (*b*). A little excess will, however, be beneficial in wetting the subsoil somewhat below the ends of the roots if thereafter moisture will arise therefrom by capillary attraction and nourish the plants; thus the advantages of sub-irrigation (Art. 10) will be secured without its disadvantages. It will be economical of supply to apply this excess if the amount thereby saved in surface evaporation exceeds that lost by downward filtration into the soil; thus, in this respect the nature of the surface and subsoils must be carefully considered. Heavy waterings prolong the period of rotation; very light ones entail much loss by evaporation; waterings of the proper amount and frequency add to the yield of the crop. Heavy waterings do not increase the yield of wheat, but light ones diminish it. In India a heavy watering varies in depth from 0·33 to 0·25 foot, and a light one from 0·25 to 0·20 foot. In Hawaii as little as 1 inch (0·08 foot) has been found sufficient.

The first watering for ploughing should be the heaviest, as then water is lost by secretion (Art. 2 (xv)) while the ground is being softened by it. The earlier waterings are usually heavier than the later ones, probably for the reason that more and more residual water is left in the soil. It is considered that the depth of individual waterings need not be according to the nature of the crops, for differences in their requirements are best met by altering the number of the waterings. As crops are grown during different periods and in different seasons, the total depth supplied to them varies considerably. Thus, taking the depth for cereals as 1, the relative depths for other crops in Northern India have been calculated to be—vegetables 1½, orchards 2, tobacco 2½, permanent forage 3, sugar cane 4, and rice (which grows in standing water) 5 to 6: the total average depth allowed for wheat is about 1 foot. In Madras (where there is good rainfall) the average depth allowed for rice is 3·7 feet. For the marcite (meadow land) cultivation of Italy and the south of France no less than 300 feet in depth is said to be given. In Ceylon rice lands are prepared for sowing by submerging them for some weeks in order to kill off the exuberant growth of weeds—this is a very wasteful process, as the weeds could be destroyed by ploughing, but this naturally entails more labour. It is said that 2 inches of rainfall occurring irregularly are equal to 1 inch of irrigation water supplied when it is required, but the variation of the first-named makes comparison difficult.

(*c*) *Number of Waterings.*—The number of waterings required has reference to the depth of the individual waterings, the nature of the soil and subsoil, the class of crop, and the season in which it is grown. It is usual on a work at first to allow waterings in accordance with the ideas of the cultivators, and thereafter to reduce them gradually as experience dictates; as the irrigated area expands this can be done with the same total supply up to a certain extent. On virgin soils it is apparently considered more frequent waterings are necessary, and as many as eight to ten have been taken for wheat grown on them in the Punjab—this is probably due to the inexperience of the irrigators, as a maximum of four, and on the average three, are generally there found sufficient.

Possibly, as virgin soils produce the heaviest crops, they require somewhat more water than old cultivated land, which also is more retentive of moisture. The experience of irrigation in America is the same, for the excessive supplies originally taken there have subsequently been greatly reduced. For sandy soils the waterings should be light and frequent, while for clayey ones they should be heavy and few.

As immediately after a watering the surface is most wet, the more frequent the waterings, the greater the loss by evaporation ; conversely, with few deep waterings more water will be lost by absorption where the soil is porous. The loss by evaporation from the ground at each watering is practically the same, and only the balance of the saturation is utilisable by the crop or is wasted by absorption.

(*d*) *Rate of Watering.*—The rate of discharge of the water admitted to irrigated land must not exceed the capacity of the irrigator to deal with it. Moreover, a very quick flow has a tendency to cause the surface cracks in the soil to get silted up, thus preventing the proper aeration of the ground. For these reasons the discharge in individual watercourses should not exceed a cusec, and may often with advantage be reduced to half that amount. The slower the rate of flow, the more water is absorbed by the upper part of the plots, and the greater is the quantity required for the whole area. On the light soils of Northern India it is reckoned that 5 acres of wheat can be watered in 24 hours by a flow of 1 cusec.

25. The Nature and Utilisation of Water.

(*a*) *Differences between Land and Water.*—In dealing with the nature of water it is advisable to consider how it differs from that of land to which it is applied for the purposes of cultivation. In this respect the principal characteristics of land are that it is immovable ; it has fixed boundaries and an unvarying extent ; it is naturally unchangeable in ordinary circumstances, but when any of its constituents are artificially removed, such as by mining, they will not be naturally replaced ; and, lastly, in most countries it is private property,

Water differs from land in all of these particulars. It has the capability of motion from one place to another ; it varies in quantity from year to year, particularly in irrigating countries, being increased by rainfall and seepage, and diminished by evaporation and absorption; thus it cannot fairly be divided between users of it in definite amounts, but must be allocated to them by shares of the fluctuating available quantity; it is not a fixed amount and irreplaceable, but is an annual supply. Lastly, except where it is private water (that is to say, is produced wholly by rain falling on private property, or rises in and does not naturally flow beyond the limits of such property) it is a national asset which in the most successful irrigating countries is vested in, or controlled by, the State for the best utilisation in the interests of all (Art. 236 (*b*)).

(*b*) *Water a National Property.*—Water in a river or stream should not be considered to be the exclusive property of the owners of the estates through which it flows, as generally it is derived for the most part from lands upstream of, or laterally beyond these. In non-irrigating countries water is usually looked upon as a nuisance to be got rid of by drainage, and is there dealt with by the Common Law[1] which secures property to individuals. In all successful irrigating countries it is regarded as a blessing to be made use of by application to the land; because of its varying amount and property of motion it is there dealt with by the Civil Law, which vests it in the State for utilisation to the best general advantage. Where, however, the Common Law is in force in an irrigating country, irrigation suffers greatly and does not progress. In such countries the riparian owners claim all the water; the upper proprietors take an undue advantage of their position; the total claims to water greatly exceed the amount available for division, and thus security of tenure cannot be obtained (Art. 239 (*c*)). The advantages of State control of water for the purposes of irrigation are that it can regulate its division impartially, and, by granting permits for its use, can arrange that the claims on it do not exceed the available supply; thus is obtained for all users that security of tenure without which irrigation enterprise cannot flourish. As the amount of water utilisable by irrigation is a limited quantity, in certain countries where Government controls the supply (notably Spain—Art. 237 (*d*)), it has been found necessary to insist that the amount available shall be used to the best advantage and must not be wasted.

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[1] Report on Irrigation, Legislation, and Enterprise, to the Government of Cape Colony, by William Ham Hall, Cape Town Government Printer.

(*c*) *Value of Water.*—Although water is a natural product, it has a saleable value for the following reasons. First, in order that it may be utilised, works have to be carried out; these are generally of an expensive nature to construct and maintain, and a charge has to be made for the use of the water to provide for interest on the capital expended and for the cost of upkeep. Next, the water is a national asset of which only a favoured few can take advantage; it is therefore right that they should pay for it so that the revenue thus derived may be applied to the relief of the ordinary taxpayer. Lastly, when irrigation is made available, the value of land to which it is furnished is increased enormously, and unless the owners thereof paid for the annual supply, they would benefit unduly by unearned increment.

26. Water Rates.

(*a*) *Incidence of Rates.*—Water rates should provide for the following:

(i) Interest on the cost of construction of the works;
(ii) Maintenance expenditure incurred on upkeep;
(iii) Charges for the actual value of the water.

It is not necessary to provide for a sinking fund, as the works when properly maintained may be considered as permanent. The cost of (i) will vary with the nature of the works and the physical conditions connected with their construction. The cost of (ii) will also vary, but probably not so greatly; it should include special repairs at intervals as well as ordinary ones. The value of water as a commodity (iii) is dealt with in Article 25 (*c*); it varies with local conditions and the price of the produce.

Theoretically, the charge for water should be in proportion to the amount applied or devoted to the fields; it should thus be greater for those having a porous soil or visited by a light rainfall than those with a retentive soil or subject to heavy rainfall; it should be less for those nearest the source of supply than those remote from it, to serve which a considerable loss in transit would be incurred. To vary the rates in accordance with the different conditions which obtain on different works, and indeed on sections of the same work, would, however, greatly complicate matters. Just as the postal and telegraphic rates of a country are the same for all parts, although the cost of the services differs considerably between long and short distances, so also is it advisable in regard to irrigation to pool results and charge uniform rates, thereby obtaining simplicity and the reduction of collection charges; extra profit from one system may thus be applied to counterbalance loss on another system. Moreover, to have varying rates for the same crop would handicap the higher-charged irrigators, unless they were otherwise more favourably circumstanced than their competitors. The one commercially justifiable variation in charge is for different kinds of crop, as they require such different amounts of water (Art. 24 (*b*)). Apart from the actual cost of the supply, however, the charge for it must bear some relation to the value of the crop matured by it. This is the practice in India, where on the average the water rate is about one-tenth the value of the crop, and in Egypt, where it is about one-seventh; in America the proportion is about one-fifth to one-sixth. The power of differentiation in charge gives the administrator a fair opportunity of encouraging the growth of crops most remunerative in return and economical in expenditure of water (Art. 12 (*e*)).

(*b*) *Variation in Rates.*—When a new work is started, the rates should be low, so as to encourage the growth of irrigation, and to counterbalance the initial heavy cost of cultivation to the irrigators. In Bombay water is often given free the first year. As experience is gained, the rates can be altered, after due notice, at intervals of a few years, so as gradually to get a fair return on the expenditure. On no account should rates be fixed in perpetuity, as the distant future cannot be foreseen, and variations in conditions, if not provided for by alterations of charges, would themselves introduce fluctuations in relative cost to the irrigators. Similarly, rates should not be fixed by law, but should be left to administration to determine in accordance with variations in conditions; legislatures do not ordinarily interfere with the law of supply and demand.

(*c*) *Measurement of Supply.*—In Europe and America, where the irrigators are advanced, water rates are often fixed by measurement, which some consider to be the ideal system, and one that should eventually be adopted in India. One difficulty is to obtain a simple automatic module which registers correctly and cannot be tampered with, and one that does not entail much loss of head or skilled maintenance (Art. 45 (*a*)). It has, however, to be remembered that water is not the sole factor connected with irrigation, as that is influenced by climate, soil conditions and rainfall. Further, the value of an unit of water in tropical countries fluctuates greatly according to hydrographic conditions, being at a maximum in seasons of drought, and at a minimum in ones of abundant supply; thus the fluctuation in value of the total supply available is small (Art. 1 (*c*) and (*d*)). A uniform rate by volume would there either be too low in the former case to repay the State for the then full value of the water, or too high in the latter to encourage the spread of irrigation, while fluctuations in charge according to the actual value of the water due to the variation of the season present many difficulties in practice. The quantity of water used depends principally upon the nature of the crop, and differences in the assessment of the crops can easily be adjusted to correspond with the variation of that quantity, while supervision and proper rotation (Art. 23 (*b*)) should be relied upon to check waste of supply and to distribute fairly the amount of water available in different seasons. Moreover, the area of crop cannot easily be disputed, whereas the supply of water by measurement may be. For these reasons the system now in force in India of payment by area of crop matured seems best adapted to the conditions there, although it involves extra work for the staff. Under that system a liberal allowance of water is permissible when the supply is good; when that is poor, it is economised so as to serve the largest area practicable, and thus to ensure the maximum general benefit.

(*d*) *Consolidated Assessment.*—In parts of India where the State owns both land and water, consolidated rates for the combined use of both are imposed on some old systems of irrigation where average conditions have been ascertained by long experience. This system has the great merits of simplicity and of the minimum interference with the irrigators. It has, however, the disadvantage that under it proper irrigation expansion does not take place when the supply is limited, as the irrigators consider they have a right to their old-established amount of water, and will not economise its use for the benefit of new lands when this is practicable by improved maintenance or methods of cultivation. In Sind

90 per cent. and in Bombay 80 per cent. of the total assessment is credited to irrigation revenue.

(*e*) *The Block System.*—Where the rainfall permits certain crops to be grown, cultivators under canals often endeavour to raise them instead of higher class ones by irrigation. The system of water rates on individual crops irrigated there tends to diminish and scatter the irrigated area, thus rendering the work less remunerative and the expenditure of water more uneconomical. To meet this in Bengal, and more recently in Bombay, what is known as the "block system" has been introduced. Under this the cultivators in arranged "blocks" of land enter into a joint lease, or agree to pay annually a through rate per acre, for a certain number of years on certain conditions as to the proportions in which classes of crops are to be cultivated in turn; supply by rotation is guaranteed for the blocks, but its detailed distribution is left to the cultivators to arrange between themselves. The blocks can be apportioned among the different villages under command so as fairly to distribute the benefits of irrigation among them, their total area is kept within the minimum irrigating capacity of the scheme, and the balance supply is utilised for extra land under ordinary crop rates. Thus irrigation is concentrated, assured, and applied to the land and for the crops most suitable for it; economy of supply is effected; interference with the cultivators and the cost of supervision are reduced; and the advantages of the systems of sale of water by measurement and of consolidated assessment (land and water rates combined) are secured.

(*f*) *The "Thal" System.*—This is the old native system which is practised in the Khándesh and Násik districts of the Central Division of the Bombay Presidency. Each village which is irrigable from a small perennial channel has its irrigation concentrated in a "thal," which consists of the most fertile area, and is generally close to the village. The "thal" is divided into a number of large plots called "phads," in each of which a single crop is grown at the same time under a long-established system of rotation. Each irrigator has allotted to him a certain area in each of the "phads," and a larger area in the dry-crop part of the village estate. Each "phad" is enclosed by a single hedge, and the individual plots in it are simply demarcated by boundary stones fixed along narrow division strips; it is guarded by the minimum number of watchmen, and water is distributed to the various plots according to a fixed time table by other village servants known as "patkeries." On the irrigated area is placed a consolidated assessment which covers both land rate and water rate, the latter being the average amount due on the series of crop rotations. The system is therefore a highly economical one in respect to utilisation of water and general supervision, and has been developed during the centuries it has existed so as to meet the general average conditions of supply, etc. The objection to it is that thereby the irrigation area is fixed and cannot easily be increased by improved methods of irrigation or by the provision of additional supply, as the original sharers consider themselves to be solely entitled to all the water available; thus progress, if not absolutely stopped, is greatly retarded.

(*g*) *Remissions and Penal Rates.*—Owing to the fluctuations of the amount of supply available in India, remissions are always granted when the crops suffer considerably from deficiency of water. Penal rates are assessed for certain breaches of the irrigation law—the scale at which these are fixed should make them deterrent, for often the unauthorised use of water is of very considerable benefit to the fraudulent irrigator, and causes much loss to those who are thus deprived of the supply to which they are entitled.

27. Experimental Stations.

On all large systems should be one or more experimental stations under agricultural experts working in co-operation with the engineering staff in order to give advice to the irrigators, and to obtain the best results from the irrigation supply. In regard to agriculture experiments should be made as to the most suitable seasons for sowing, superior methods of cultivation, the best crops to grow and the value of their produce, the most remunerative manures to use, etc. Soil analyses should be made, the effect of the rainfall on the crops noted, and the cultivators instructed how best to market their out-turn, and in the advantages of co-operation. In respect to irrigation experiments should be carried out as to the number, frequency and depth of waterings required, and as to the results of absorption, evaporation and drainage; and analyses of water should be performed. The engineering staff should make experiments on duty in regard both to small individual plots and to extensive areas, and determine the rise of subsoil water and other hydrographic particulars (end of Art. 4).

From the data thus obtained improvement in the methods of agriculture and irrigation should gradually be attained; it should be remembered that the cultivator is conservative in his ideas, and therefore should be led, not forced, to adopt improvements; further, that what succeeds on an experimental station under skilled superintendence and with a comparatively large amount of capital, may not be practicable, or may require modification, on the ordinary irrigated area worked by simple farmers with little money to risk.

In the United States of America, in some of the Colonies, and recently in India, further progress is made in development by means of the issue of bulletins of instruction, itinerating demonstrators, agricultural shows, etc.

CHAPTER II.

MISCELLANEOUS.

28. Assimilation of Full-Supply and High-Flood Levels.

(*a*) *General Remarks.*—A work for the storage of water has to be designed to be safe at high-flood level, and not only at full-supply level. The necessity for providing the margin of safety between these two levels involves what may be considered either as an expensive, but essential, addition to the cost of the work, or as a surrendering of a large amount of storage. To utilise this extra expense by securing additional storage, the design should provide for raising the full-supply level to high-flood level after the flood season is over. As, however, an abnormal flood may arrive after this has been done, the design must also permit of discharging such a flood without incurring any risk to the work and of impounding its tail flow so as to regain the increased storage capacity previously run to waste.

(*b*) *Temporary Crests.*—In the case of dams and storage weirs this assimilation of the two levels can be effected at the end of the flood season by erecting on the permanent crest of the waste weir a quick-acting temporary crest of shutters, or automatic sluices, or both, and by having a series of deep-seated sluices.[1] These should have discharging power sufficient to keep the surface of the reservoir low during breaks in the flood season, and thereafter to lower it a short time before the advent of a subsequent flood, in order to give the storage what is called "flood-absorptive capacity," and so as to permit of the removal of the temporary crest in the dry. The full-supply storage capacity of a reservoir is generally very large when compared with the initial discharge of a flood; it is only when this condition obtains that such raising of the full-supply level should be attempted. Ample time for working the design will thus be available, but to ensure this it is essential that the sluices and temporary crest should be quick-acting, and that they should be of a simple character, so that their action cannot be retarded by floating *débris*, rust, etc. Automatic gates, opening when the designed high-flood level is exceeded, and closing when the reservoir surface falls below it, are useful; but as they are expensive, additional undersluices may safely be substituted for them, provided that a continuous, careful watch is maintained during the comparatively short period when dangerous abnormal floods may occur at the end of the flood season, when only the extra temporary storage is being effected. It is not advisable to make the temporary crest more than 4 feet in height.

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[1] "Indian Storage Reservoirs," by the Author, second edition, pp. 223–241, Spon & Co.

A converse state of affairs occurs when the storage of a work has to be maintained normally at a certain level which must not be exceeded during a flood, e.g. a reservoir in an urban or other area which must not be further submerged, and a diversion weir (Art. 2) with a raised temporary crest. For such a reservoir a temporary shutter crest, not exceeding 4 feet in height, large undersluice discharging capacity, and also numerous automatic gates, should be provided. For such a weir the temporary crest should not exceed 6 feet in height, and should be capable of being very quickly lowered. This is effected in Northern India by releasing, one after the other by means of a wire rope laid overhead as a continuous band with a button fixed on it, the triggers at the tops of the back struts, each of which supports a shutter forming part of the crest. To assist in lowering the crest and in impounding the tail flow of the flood, large and deep undersluices should be provided. In weirs on alluvial soils another advantage of being able to release all the crest shutters nearly simultaneously is that thus are avoided cross currents downstream from the open to the closed section, which would endanger the toe of the work by undermining it.

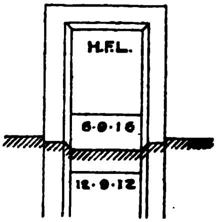
(*c*) *Cross-Drainage Works.*—When designing a cross-drainage work, the high-flood level of the stream has alone to be considered, as, owing to the fluctuations of its discharge, there is no full-supply level. Ample provision for the safe discharge of floods must be made initially, as additional discharging capacity cannot subsequently be at once obtained (Art. 150).

29. Engraved Record on Masonry Works.

(*a*) *High-Flood Marks and Record.*—It is desirable to have cut on masonry works certain records so that they may be referred to during inspection. In the case of cross-drainage works the most important record is that of the heights to which abnormal floods rose; this should be made so as to last for a long time, and should include the observations of many years. When the work is built of fine-grained durable stone it will suffice if a shallow recessed area is dressed for this purpose, and has engraved on it dated lines corresponding to the different important flood levels, and at top the letters H.F.L., which will apply to all such levels (Fig. 4). When the work is constructed of coarse-grained or soft stone or brickwork, a slab of fine-grained, durable stone of sufficient length should be securely built into it for this purpose. The high-flood tablet should be placed where it is easily visible, but it should be out of the main current (e.g. on a downstream wing wall), so that it may record the correct levels of the unobstructed floods; these levels should be most carefully observed by experienced men. A register of high-flood marks is desirable; one for a canal or road might be maintained in a tabular form, thus:

FIG. 4

FLOOD TABLET



1. Mileage of work.
2. Number of work.
3. Description of work (bridge, 3 spans of 30 feet).
4. Date of flood.
5. Height of flood in feet above or below springing.
6. High-flood mark where engraved.
7. Name of observer.
8. Date when recorded.

(*b*) *Other Marks.*—The distinctive number of the work and the year in which it was constructed might be engraved on the downstream face and at the centre of the downstream parapet wall; the mileage of the work above this on top of the parapet coping; and a benchmark on top of an abutment.

(*c*) *Construction of Marks.*—An engraved tablet should be slightly recessed below the general face of the masonry, and may with advantage be surrounded by a simple chamfer or moulding as a frame, so that it will appear as an integral part of the structure. If it projects beyond that face, it will look like an added excrescence.

The engraving is best done as V-shaped cuts, so that the arices may be preserved; if these cuts are leaded, they will be more permanent. Stencil plates should be used for marking out the work so as to ensure neat figures, etc., of the same character throughout the project.

30. Oblique Weirs.

Certain weirs have been built in plan curved or oblique to the stream with the object of increasing their discharging capacity by adding to their normal length. Such an increase of length will diminish slightly the flood depth over the crest itself, but will thus induce a greater velocity of approach to it; the head thereby consumed will practically be equal to the diminution of the flood depth over the weir crest, and the flood level some distance upstream will therefore not be sensibly lowered. Were this artifice of increasing the length of the work effective, it could be developed greatly by making the weir deeply serrated in plan. Designs of this character have been constructed in America, but have there been found not to increase the discharging power much beyond that of straight weirs having their flanks the same distances apart normally. The increase of length will add to the cost of the work unless the nature of the foundations lends itself to the design; that would be the case were these higher on an oblique than on the normal alignment.

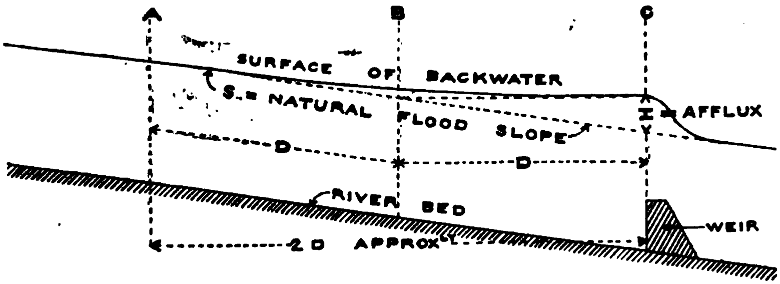
An oblique weir with a level crest tends to divert the current of the stream to its upstream flank, where the overfall first takes place, and thus aids in preserving a deep channel there which may be desirable if the canal is led off from that side. The same effect can more cheaply and easily be produced by lowering the crest slightly from the side remote from the regulator. These devices can safely be adopted only where the river bed is of hard, unerodible material—where it is soft, parallel currents will thus be set up which will tend to undermine the weir. For such weirs it may be objectionable to produce both a deep channel at one side and a raising of the flood level at the other side, as it is generally better to have a flow of even depth over the whole length of the work. If the river carries much silt, the formation of a deep current in it next the regulator will bring more silt into the canal.

31. Weir Backwater Afflux Curve.

A weir causes an afflux, or raising of the river surface, above it of a height proportionate to the depth of the discharge The flood surface of the river in the backwater of a weir rises as a gentle asymptotic curve from its level at the crest of the work until it meets the normal flood level at some distance upstream, for the flood discharge while approaching the weir must have a slope to produce its velocity. A close approximation to this asymptotic curve can be drawn as shown in Fig. 5,

FIG. 5

DIAGRAM OF AFFLUX



where H is the afflux height over the weir at C;

D, the distance from C to B, the point where the original flood slope of the river is cut by a horizontal line drawn through the top of H; and

S, the natural flood slope of the river.

Then the backwater afflux will meet the original flood slope approximately at A, which is determined by making AB equal to BC, so that A is approximately 2D from the weir. The entire curve can be drawn approximately as a segment of a circle meeting A and C tangentially to the setting out lines there.

$$\text{As } \frac{H}{D}=S,\ D=\frac{H}{S} \text{ and } 2D=\frac{2H}{S}.$$

The assumptions not being quite accurate, a little extra allowance should be made for the margin of safety which should anyhow be provided for abnormal floods. All marginal land up to a level a little above the curved line ABC should be acquired, as during high floods most of it will be submerged by the construction of the weir, and crops growing on it may thus be injured. Where practicable, it should be planted out with trees, so that revenue may be produced by the sale of their timber or produce.

Where the backwater is confined by flood embankments, these should be retired beyond the probability of erosion, and should be raised not less than 5 feet above the calculated backwater afflux.

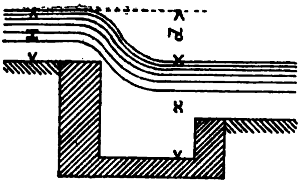
32. Water Cushions.

(*a*) *General Remarks.*—In Nature the base of a high waterfall is protected from further scour by the formation of a deep pool in which the energy of the overfall discharge is destroyed by the body of water in the pool. As the excavation of a large volume of hard material is expensive, man has imitated this plan more cheaply by forming a water cushion by means of a weir built some distance below the main overfall. In India the water cushion has been found to be a most effective preventive of scour, and much superior to an ogee slope (Art. 211 (*d*)).

A water cushion forms the best kind of protection below a high weir and below the undersluices of a masonry dam; for the latter it will have the additional advantage of providing the means of gauging the discharge passed down. Below a storage weir with numerous undersluices, if the water cushion is divided into two or more basins by cross walls parallel to the flow, each such basin can, when necessary, alternately be laid dry cheaply, and the foundations of the masonry can be examined and repaired without shutting off all the discharge. (See also Art. 225 (*c*).)

FIG. 6

WATER CUSHION



(*b*) *Formula for Water Cushions.*—The depth of the pool should be designed with reference to the nature of the foundation to be protected (Fig. 6).

For soft soils the usual formula (Dyas) adopted is:

$$x = \sqrt{H}\ \sqrt[3]{d}$$

where d = the depth of fall from the upstream to the downstream surface;
H = the height of the afflux upstream; and
x = the depth of the water cushion.

For harder soils the depth may be reduced, until for rock or good stone pavement x may be made one-quarter of d.

The length l of the water cushion for soft soils is given by Dyas as $= 2\sqrt{Hd}$; it may be reduced similarly for harder material in the bed.

(*c*) *Design.*—For soft soils the crest length of the water cushion downstream cross wall should not be much less than the width of the channel downstream, so as to distribute the flow evenly down it, and thus prevent scour; the best proportion is that the former should be seven-eighths of the latter. In hard soils, and especially rock which can safely withstand the action of a quick current, the crest length may be reduced considerably so as thereby to increase the depth of the water cushion.

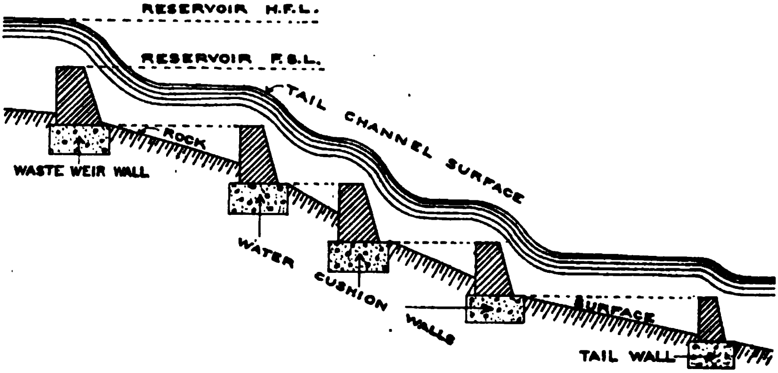
If the main weir is a low one, and boulders are liable to be carried over it, the length of the water cushion should be increased, and the water cushion downstream cross wall should be replaced by a paved slope rising gently (from 2 to 5 to 1) downstream so that the boulders may be swept over it and may not be retained in the water cushion, where otherwise they would be caught by eddies and would scour out potholes. With high weirs boulders are not likely to be carried forward, as they will probably be trapped in the upstream backwater pool.

The further development of the water cushion wall is to raise its crest so much that it substantially divides the total overfall, when that is considerable, with the main weir. The ultimate stage is reached when there is formed a series of water cushions over which the water cascades, e.g. from the waste weir of a deep reservoir to the natural drainage line of the country below (Fig. 7).

This raising of the crest of the water-cushion wall should be effected only when the bed material is sound; where that is soft, the water cushion should be excavated wholly below the level of the downstream bed, and the water-cushion wall should be replaced by a gentle reversed paved slope up which the water will pass as a slow, steady current which will not cause scour downstream (Fig. 8). The excavated material can frequently be utilised in the formation of neighbouring embankments.

FIG. 7

WATER CUSHIONS IN SERIES

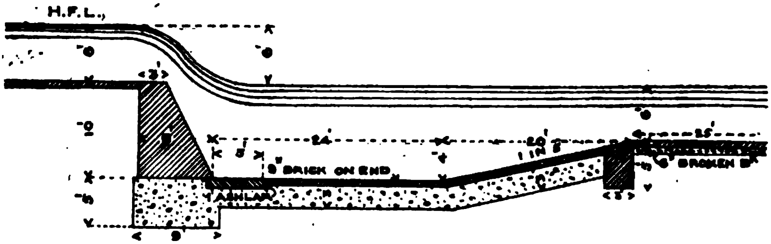


33. Aprons.

A paved apron is another form of protection of foundations; here part of the energy of the overflowing water is destroyed by the friction of the surface of the apron. If the pavement is not able to resist this action, portions of it will be carried away, and the result will be that the water will there gain

FIG. 8

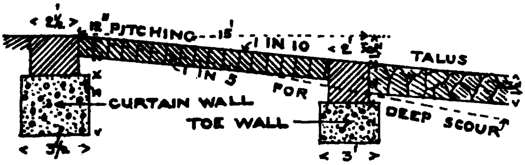
WATER CUSHION IN SOFT SOIL



increased power to continue the process of destruction unless repairs can early be effected. An apron is thus not very suitable where there is a long-continued rush of water, such as takes place at river undersluices kept open throughout the flood season. It is better adapted to cases where the flow is comparatively gentle or short-lived, such as generally occurs under cross-drainage works, and here the design has the advantage that it does not much retard the velocity of the flow and thus necessitate an increase to the flood waterway. The slope of the apron for such foundations should be continued well beyond the probable limit of scour, and should be finished off with a toe wall carried some feet deeper, so as to prevent any danger of undermining, which, if it occurred, would probably soon destroy the structure. The apron of a cross-drainage work should start from a curtain wall built across the stream bed at the downstream end of the abutments or wings, and, where necessary, its own toe wall should be protected downstream by a talus of boulders, concrete blocks, etc. (Fig. 9).

FIG. 9

CROSS-DRAINAGE APRON



A paved slope is also suitable and economical for the case of the discharge of a thin sheet of water down a considerable vertical distance, and where the foundations are inferior: it then becomes a "rapid" (Art. 145).

An apron is a most essential part of the design of the Bell bund (Art. 185): there it constitutes a sidelong and not an endwise protection. The long-sloped weirs on sand foundations (Art. 213) may be considered to be the ultimate development of the apron system, whereby water is passed down a slope from a high to a low level. At the base of an apron on soft foundations a small natural water cushion is generally formed; conversely, the pavement of a water cushion may be considered to be a subsidiary apron.

34. Dams with Overhung Batter.[1]

It is a common but erroneous idea that a masonry dam is given greater stability against the overturning movement of the water pressure upon it by building the upstream face with a positive or outward batter, the supposed greater stability being due to the vertical component of the water pressure on this battered face.

If a comparison is made between—

(i) a dam with a vertical upstream face, and
(ii) one having the same base, crest-width and height, but with the crest shifted a little downstream so as to give a positive batter upstream,

it will be found that in (ii), in consequence of the upstream batter, the moment of resistance to overturning (due to the weight of the masonry) is decreased as the centre of gravity is moved horizontally away from the upstream face. That resistance is, however, increased by the vertical component of the pressure of water on the battering face. The design must not let the centre of total pressure fall outside the middle third of the base. If moments are taken round the extreme edge of this middle third, it will be seen that in every conceivable case (except that of a dam very largely constructed of timber) the positive batter reduces the gravity stability of the dam against overturning, as masonry always weighs more than twice as much as water.

A similar demonstration will make it equally clear that a small negative, or overhung, batter will increase the stability of the dam for the same quantity of masonry; the overhang has to become large before the increase of stability reaches its limit. This is on the assumption that the dam is subjected to full water pressure up to its crest. When, however, the water is withdrawn, the design must still keep the centre of total pressure within the middle third of the base, and that must not pass beyond the upstream edge of this middle third. This condition fixes the limit of the amount of overhang permissible.

In practice it will generally be best to build the upstream face of a weir vertical (Art. 133 (*d*)), as an overhung batter may induce silting at the weir. The upstream batter usually given to the dam increases the difficulty of construction at the undersluices, as the lifting rods from these usually travel up and down a vertical face, which for such a dam has there to be specially constructed for them.

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[1] *The Engineer*, Vol. CIX., No. 2,839, May 27, 1910. (Mr. Robert E. Smith.

35. Sluices.

(*a*) *Effect of Sluices.*—It is generally supposed that a sluice, even if small, has a considerable silt-clearing capacity. This, however, is not the case, for when it is submerged the inflowing water approaches it, not normally, but in a fan-like direction in all planes. The cross-sectional area of the approach flow at a short distance from the sluice is thus very much greater than that of the sluiceway itself: hence the velocity of approach there is practically *nil*, and consequently is not able to carry previously deposited silt through the sluice. When the sluice is not submerged the approach flow has a smaller cross-sectional area and a somewhat greater velocity, but this is not sufficient to move silt at any distance upstream of the sluice. Speaking generally, a sluice is not able to keep clear for any appreciable length a channel with a cross-sectional area much greater than its own. To make it more effective, a training or "divide wall" (Art. 213, end of (*a*)) should be constructed upstream of it parallel to the line of flow so as to direct that to it.

The effect of a sluice downstream of it may, however, be very considerable owing to the concentrated discharge of a long-continued flow at high velocity which will rapidly scour any unprotected soft soils; such a soil is best protected by a water cushion constructed just downstream of the sluice, which will absorb much of the energy of the rapidly moving water.

It will thus be seen that undersluices in the dam of a large reservoir have the smallest direct silt-transporting power; their utility for the reduction of deposit consists in the fact that water cannot silt above its own level. By keeping such sluices open during the early part of the flood season, when the greater part of the silt is carried into the reservoir, the basin is maintained at a minimum size, and the time during which deposit takes place is correspondingly reduced. To prevent the sluices from being interfered with by *débris*, gratings of old rails should be fixed between the sluice piers and some distance upstream, so as to give working space between the gratings and the sluices.

(*b*) *Sluices for Weirs.*—Sluices in waste weirs are unnecessary for silt clearance, as there the deposit is very little. They may be wanted if a high-level irrigation channel is taken off so as to utilise water which would otherwise spill over the weir to waste. They may also be required to aid in increasing the discharging capacity of the weir, and when low-seated to bring the reservoir flood-absorptive capacity earlier into action.

For weirs on non-alluvial rivers the sluices may be comparatively small, as these streams carry little silt, but in all cases it is better to have considerable sluice-discharging capacity. For weirs on alluvial rivers the undersluices should be large to deal with the great amount of silt carried. For both classes the undersluices should be placed near the head regulator of the canal, so as to preserve a deep-water channel leading to it. The sills should be as low as practicable, so as to increase the depth and length of that channel, and to diminish the overfall action of the water on the bed downstream. Large sluices are especially necessary in the case of rivers liable to bring down trees and timber, for openings of even 30 feet span have been choked thereby.

The ultimate development of sluices is to form the weir as an arcade, the vents of which are kept open in the flood season, and are closed by gates or shutters during the fair one ; this is the only form of weir which does not greatly obstruct the flow of the river, and thus does not tend to cause the bed to silt up rapidly.

(*c*) *Construction of Sluices.*—Small sluices should be of cast iron faced with gun metal, and should have their largest dimension vertical, so as to increase the bearing on the frame and lessen the total water pressure on any cross-section—this will also make the travel of the sluice smoother. Such gates move between cast iron frames, similarly faced, and guides. They are actuated by means of lifting rods passing through plummer blocks to preserve their verticality, and the tops of the rods are usually cut to form screws which pass through female screwed blocks in capstan heads ; these capstans are carried on jack arches so as to obtain rigid support.

Larger sluices may be of cast iron, or be built up with frames and plates. The friction in working them should be reduced by means of roller bearings or counterpoises. In all cases ample lifting power should be arranged for, to provide for the possible jamming of the sluices.

The undersluices of large weirs on alluvial rivers are noticed in Article 217, automatic gates in Article 28 (*b*) and regulator gates in Article 46 (*c*).

36. Scouring and Transporting Power of Water.

Tables are given in books of the minimum velocities which will move particles of different size and specific gravity, but these appear to be based generally on laboratory experiments which do not fully represent natural conditions. The following values are noted as rough approximations of the maximum mean velocities in feet per second which will not scour:

Soft light soils	1·0
Ordinary clayey soils	2·0 to 3·0
Soft gravelly soils	3·0 to 4·0
Hard gravelly soils	4·0 to 5·0
Soft rock	5·0 to 8·0
Hard unfissured rock	8·0 to 20·0

(See also Art. 115 (*a*).)

The velocity which is sufficient to detach particles from their bed will be greater than what is necessary to transport them. The scouring power of water tends to overcome the resistance due to cohesion, and varies as the square of the velocity of the current: the transporting power of water tends to overcome the resistance due to weight, and varies as the sixth power of that velocity. The resistance to scour and transportation of slightly cohering soils is a mixed one, and will vary between the square and sixth power of the velocity. The resistance to transportation is lessened by the fact that the submerged material loses weight equivalent to the weight of the water equal to its volume; thus material with a high specific gravity offers the greatest resistance to transportation. The nature of the material also affects its power of resistance to scour—a very greasy clay will stand a comparatively high velocity; a gritty soil, giving the water a hold on it, will be moved by a somewhat low velocity; jointed rock, if exposed to cascading action, may be disintegrated by the hammering of the overfall.

It is, however, not the average velocity of the water which has to be considered, but its maximum one, as that will attack and scour the bed where it occurs and lead to further deepening by the concentration of flow it produces. This is especially the case in channels of great width, such as those of waste weirs, where scouring will first take place where the bed is soft, and thus lead to the destruction of harder parts. In such cases it is advisable to limit the velocity a good deal below that which the material of the bed will stand if exposed only to regular flows, and to stop scouring by placing boulders at the head of scour channels, or in bad instances by constructing curtain walls across the entire main channels so as to equalise the flow of floods down them (see Art. **116** (*b*), "retrogression of levels").

37. Foundations.

(*a*) *Action of Water.*—With respect to foundations, what the irrigation engineer has chiefly to fear is the possible action on them of water. Leakage under a masonry dam will tend to buoy it up and lessen its weight; large vertical fissures should therefore be opened out and filled with fine cement concrete or masonry, and small ones grouted with cement mortar; horizontal fissures should be cut off by key trenches carried below them and filled with fine cement concrete. Leakage under an earthen dam may saturate its base and make it too soft to carry the superstructure. It should be cut off by means of a puddle trench, the bed of which, if of rock, should be made water-tight as described above. In all dams the nature of the strata underlying the foundation should be ascertained by excavating trial pits through them for some depth, so that a knowledge of the sub-foundation conditions may be gained.

(*b*) *Precautions at Certain Works.*—Weirs and escapes are especially subject to undermining by the concussion of the water on the foundations, which, if of fissured rock, are liable to have the rock removed piecemeal in blocks. These works must always be securely founded well below the limit of scour by the water, or have their foundations protected by water cushions.

Piers and abutments of cross-drainage works have to withstand a considerable swirl of water, particularly at their ends; their foundations should therefore be carried into rock, if practicable, or if that does not exist, well beyond fear of scour, especially at their ends; or should, when necessary, be protected by curtain walls, both upstream and downstream, to equalise the flow of the whole waterway, and by aprons downstream to convey it safely and regularly away from the works. The aprons should have a steep downwards slope, so that their downstream ends may always be covered by natural water cushions, and, when advisable, these ends should be protected from scour by tail walls carried across the beds of the waterways. The curtain walls are best built a little beyond the ends of the piers, so that any future repair or underpinning to them can be carried out without affecting the superstructures of the main works. These protective arrangements, by equalising the flow of the whole waterways, prevent the formation of scour channels, which would gradually deepen by the concentrated flow down them.

(c) *Constructional Details.*—Wing and return walls, which are retired from the direct flow of floods, for the sake of economy may have their foundations stepped up from the abutments in steps each not exceeding 2 feet in height nor less than 5 feet in length; shallower steps may have less length. It is as well to make the steps of the concrete foundation and those of the base of the masonry break joint with each other in longitudinal section, so as to distribute the pressure of the superstructure more evenly on the soil (*vide* Fig. 66, p. 287).

Where the foundation is naturally hard enough to carry the work, but is liable to erosion, sufficient protection may be given to it by continuing the masonry only as a facing strip on the water side down to a safe depth. If that depth is considerable, the facing should be backed by a strip of concrete (*vide* Figs. 33 and 35, pp. 196, 197), which may be either of the full or of reduced width, in accordance with the degree of hardness of the soil; the reduction of width in good hard foundations, of course, tends to economy in the cost of construction.

The lowest part of the foundations (particularly those of weirs) should be constructed first, and the superstructure carried up therefrom in level stages. If the work is built in the dry, this will secure its regular settlement, and the longest time for the highest parts of it to set; if the foundation is subject to infiltration by springs, etc., the additional advantage thus gained will be that the water pressure to be dealt with during construction will be at a minimum, and the upper parts can be founded in the dry.

Foundations should usually be of concrete, partly for the sake of economy, and partly because this material completely fills the excavation. Where the face of the foundation is subject to the scouring action or overfall of water, it is best to protect it by masonry facing.

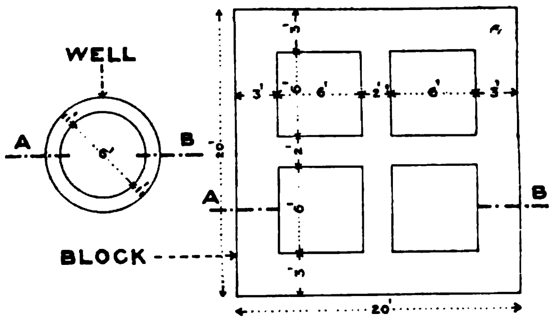
Concrete foundations should never be less than 1 foot in thickness, and preferably not less than 1½ feet, as, if they are thinner, the material may crack under the weight of the superstructure. The depth and width of the concrete foundation should be sufficient to enable it to carry the superstructure with safety, and the concrete should rest on reliable natural material.

Where subaqueous foundations are enclosed during construction by ring banks, the latter should be set well back so as to get plenty of working area. A good rule to adopt for this is that a line drawn from the bottom outer edge of the foundation to where the surface of the exterior water produced meets the inner slope of the ring bank should not have a slope less than 1 in 10.

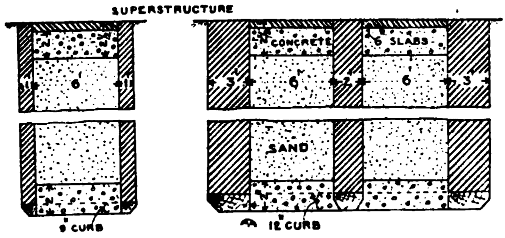
FIG. 9A

WELLS AND BLOCKS

PLANS



SECTIONS ON AB



(*d*) *Well and Block Foundations.*—In alluvial soils, and especially where these are charged with water, the foundations in India usually take the form of wells or blocks in rows. A well consists of a masonry or brickwork ring built on a curb; a block is a rectangular mass enclosing spaces to lighten and cheapen it (Fig. 9A). Wells and blocks are generally commenced at spring level; if they have to be built in water, an artificial sand mound is usually made in this, and the work started thereon. The structures are raised a certain height, and afterwards are caused to sink by excavating their interiors and increasing their height and weight until they reach the desired foundation level. A plug of concrete is then formed at the base of each of the interior spaces, and over it sand is filled in. The top 2 feet of the interior and of the external excavation crater are finally filled with rubble masonry and slabbed over to form the foundation of the superstructure. Another way of filling an important well is shown in Fig. 130, p. 507.

In modern railway practice in India iron caissons are sunk by the pneumatic process and large excavation grabs, and have been carried down 100 feet and more below river bed level. For the foundations of irrigation works such depths are unneccessary, as they are protected from scour by long aprons or platforms.

38. Retaining Walls.

(*a*) *General Remarks.*—Retaining walls have to withstand the pressure of the earthwork behind them, which is not necessarily normal to their inner face. That pressure will be greatest when the earthwork is formed in layers sloping to the wall, and least when it is in layers sloping away therefrom. If the earthwork is very clayey, and is simply placed as a loose mass of clods, it will absorb much water from rainfall, etc., and, when fully saturated, will exert hydrostatic pressure. The pressure of the bank is reduced by the cohesion of its earthwork, which is at a maximum when the material is only slightly damp; it is thus most essential that the backing should not become saturated nor quite dry. The best arrangement is therefore to form the backing of self-draining material equivalent to, say, 1 of pure clay to 2 of pure grit, with a surface cover of, say, 3 feet of water-tight soil; to lead all excess water from the bank out of the wall by means of weep holes near the base of the structure; and by a catchwater drain to prevent the soakage of surface drainage behind the wall. The wall should be considered to be a protection of the backing from the weather rather than as a dam retaining it.

The chief cause of failure of retaining walls is not due to inherent weakness of their sections, but to defective foundations, which cannot sustain the unequal pressures transmitted to them at their base. Foundations which become soft under the action of water are particularly dangerous, and retaining walls should therefore be founded on soils which are incompressible or only slightly so even when saturated—this applies of course with particular force to irrigation works. The foundation courses should project well beyond the front face of the wall, so as to distribute the pressure on a large base and more equally on it by bringing the centre of resistance nearer to the middle of the base than it is in the body of the wall.[1]

(*b*) *Empirical Rules.*—Although there are many theoretical investigations as to the stability of retaining walls, the conditions are so varied that the calculations are not of much utility. Ordinary retaining walls are therefore generally designed by practical empirical rules, of which some are given below:

(i) The thickness of the wall at any height to be slightly greater than three-sevenths of that height or one-third of the height in feet *plus* one.

(ii) For masonry walls the top width to be one-sixth of the mean height measured from the base of the foundation and both batters 1 in 6.

(iii) For masonry walls the mean width of the mean section to be at least three-elevenths of its height, and for brick walls at least three-tenths of its height. Back, vertical, and front batter 1 in 8.

(iv) Sir Benjamin Baker[2] states the mean thickness of a wall with a front batter of 1 in 12 to 1 in 6 need not exceed one-quarter of its height.

(v) General Fanshawe's[3] rules for brick walls retaining ordinary material is that the mean thickness of walls with different front batters should be the following percentages of their heights:

Front batter 1 in.—	5	6	8	10	12	24	vertical.
Mean thickness, percentage of height —	24	25	26	27	28	30	32

Fig. 10[4] shows how the batters influence the thickness of the section. Mr. Bligh says that in these sections the centre of pressure falls close to the outer toe, i.e. at one-eighth of the base from that point. If the wall is of brickwork, the centre of pressure will fall about one-tenth of the base from the above one-eighth point. Such a wall will be safe, but to make it as strong as the stone wall the base should be increased from 6 inches in the higher to 4 inches in the lower sections, right through. For simplicity in setting out works, the ratios of the batters should be fractions of 12 (inches in a foot), instead of the complicated ones of the Figure, which involve for construction the preparation of tables of course widths.

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[1] Rankine, "Civil Engineering," eighth edition, 1872, Art. 271, p. 409.

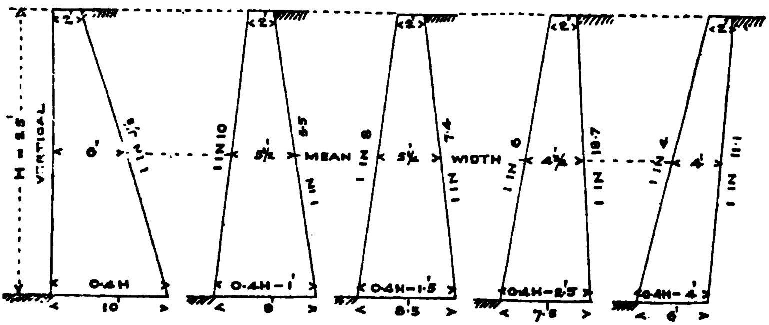
[2] Minutes of Proceedings, Inst.C.E., Vol. LXV., p. 183.

[3] *Ibid.*, p. 184.

[4] "The Practical Design of Irrigation Works," second edition, 1912, p. 15, by W. G. Bligh, M.Inst.C.E. Constable & Co.

FIG. 10

SECTIONS OF RETAINING WALLS



WEIGHT PER C.FT—EARTH, 112·5 LBS; MASONRY, 131·3 LBS

(*c*) *Design and Construction.*—The increase of the front batter adds to the stability of the wall, and thus permits its mean thickness to be reduced. Thus for ordinary walls it is advisable to have the back vertical, and to put all the batter on the front; for walls which have to be in water-tight connection with the backing a rear batter is, however, necessary to ensure that connection during and after the settlement of the earthwork. Where neither infiltration from water nor settlement of the backing from the wall need be feared, the back may be given a small reversed batter (Fig. 27, p. 177), so that the wall resists the earth pressure actively, and not merely passively, by its weight. As the pressure of the earth is concentrated towards the front face of the wall, that face should be formed with the best stones well tied into the backing, which may be of inferior masonry or brickwork, or even, in small walls, built dry. The back should be made rough in an ordinary wall so that the earth may not slide on it; if built in steps, the weight of the earth resting on these will add to the stability of the wall.

39. Wing Walls.

(*a*) *General Remarks.*—A wing wall is the most usual form of a retaining wall. In plan it may be of different shapes (Fig. 11). A guiding principle in hard soils, and also where the velocity is great, is that the tail end should be retired beyond the direct rush of the stream through a cross-drainage work, so that the toe of the canal bank may not be eroded. If, however, it requires protection, that may be given by pitching the slope. A wing wall has two further main purposes to fulfil—the support of the canal embankment and the direction of the water through the cross-drainage vent. A curved wall concave in plan to the stream offers the greatest resistance to the pressure of the earthwork, but may cause eddying motion; it is therefore best adapted to a site where the soil is hard and the embankment high. A curved wall, convex in plan to the stream (Fig. 131, p. 508), requires to be increased in section to resist the earth pressure, but leads the water smoothly and regularly to the cross-drainage vent; it is thus most suitable to a site where the soil is soft and the canal bank low. A straight wing wall splayed from the current is also a weak form, and although it directs the water to the vent, tends to divert the flow to the opposite side, which may lead to unequal scour and irregular motion downstream where the soil is soft.

(*b*) *Forms of Wing Walls.*—A quadrantal plan is the strongest, and in appearance the boldest one, but it involves extra trouble and cost in construction. For large works the best design is one in which the wing in plan is a segment of a circle to the inner edge of the top of the canal embankment, and is continued thence with a splay. (See also Fig. 68, p. 294*a*.)

Straight-splayed wings are frequently built with a splay of 1 to 1, which increases their length and thus their cost beyond what is usually necessary. As a rule a 1 to 3 splay is sufficient and considerably cheaper. Long wings have the advantage that they prevent the creep of water along them

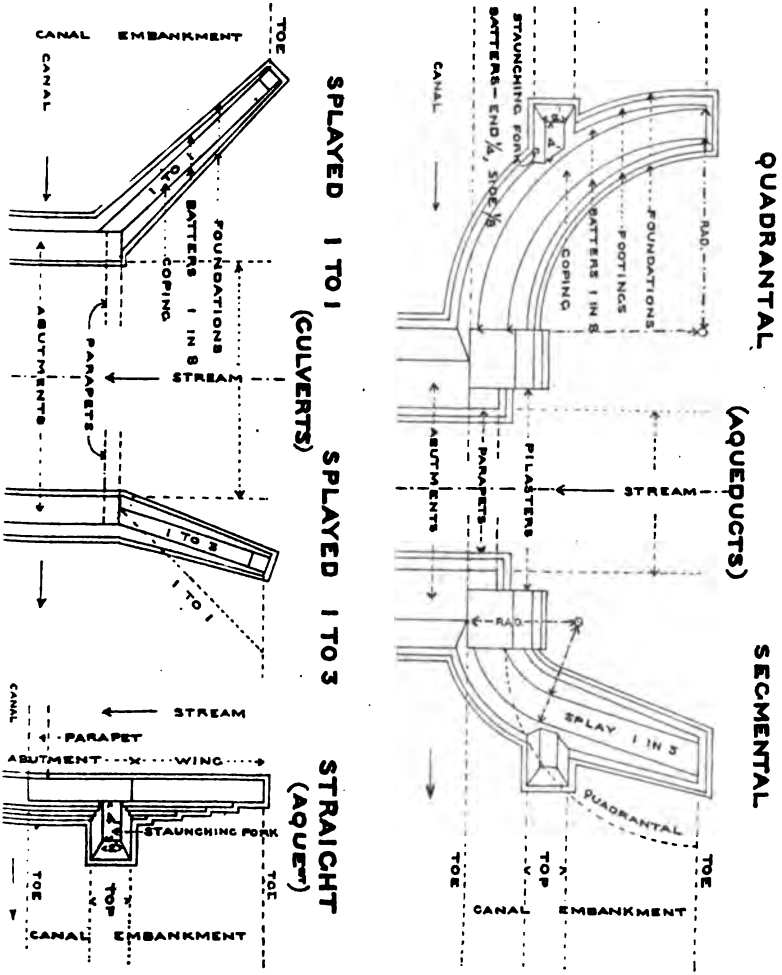


FIG. 11

TYPE PLANS OF WING WALLS

better than do short ones; the former should therefore be adopted in very pervious soils.

Where the current is not a violent one, the wings may be built in continuation of the abutment. (See also Fig. 69, p. 296*a*.) This is the cheapest form; it is also the best one to adopt for works in alluvial soil, because it directs the downstream flow of the stream straight from them, and any potholes which may be formed by eddies will be made some distance below them, and will thus be harmless to the works. Divergent wings considerably increase the flood waterway immediately below the works, and thus produce irregular flow and eddying motion which in alluvial soils tends to cause the formation of scour holes dangerously close to the structures. (See also Art. 225 (*c*).)

(*c*) *Details of Design.*—When practicable, wings should be situated on high ground, so as to reduce their length and cost, which may otherwise be considerable (see Fig. 68, p. 294*a*), and the height of the flank embankments. Where their splay is small, additional protection from flood scour can be given to the flank embankments by constructing low return walls at their toes—this arrangement will be cheaper and as safe as a design having wings built with a large splay. Return walls from the abutments cannot, however, be substituted for the entire wings of aqueducts, as thus in plan space would not be provided for the canal banks, unless the abutments were extended some length for the purpose. Such walls might be built for culverts, but it is not the usual practice to construct them even in hard soil for these works. The toe of an embankment where it meets a wing wall should be pitched up to 2 feet above the high-flood level of the stream to protect the earthwork from erosion, wave-wash, etc.

40. Staunching Walls, Forks, and Rings.

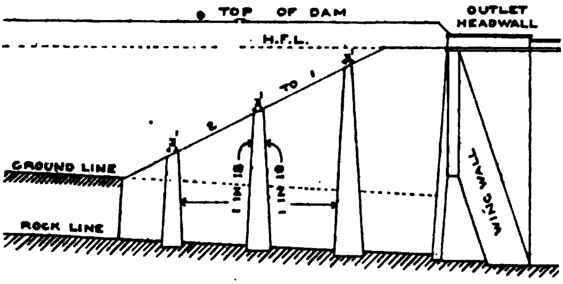
(*a*) *General Remarks.*—When water passing through comparatively permeable earthwork meets practically impermeable masonry, it has a tendency to creep along the face of the latter in order to gain an exit. If it succeeds in doing this, a leak outflanking the work is likely to be formed, and therefore this tendency must be resisted. The earth backing should be sufficiently clayey in composition and wedge-shaped in section so that it may be pressed water-tight against the masonry during and after its final settlement in order to prevent the formation of any open space in which the infiltering water would gain hydrostatic pressure.

(*b*) *Staunching Walls.*—The staunching wall should be as long as practicable, so as to increase the length to be traversed by the creeping water and consequently the resistance to its flow. The length should be in proportion to the amount of water pressure to be withstood (Fig. 12). If this wall is low and the earth behind it is not subjected to much pressure, the back face of the masonry should be left rough, so as to bond the two materials together, provided always that there are not any projections extending so much beyond the lower part of the wall as to cause vacuities in the earthwork to be

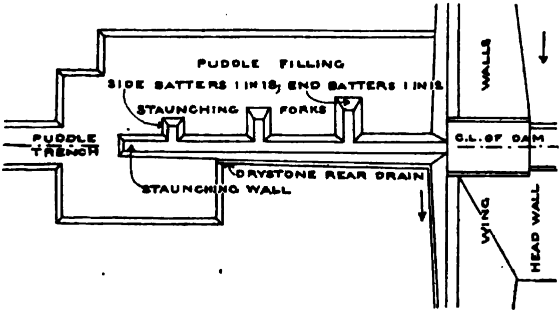
FIG. 12

DAM OUTLET STAUNCHING WALL

ELEVATION



PLAN



formed there during the settlement of the backing. If the wall is high and the earth behind it is thus likely to settle considerably, the back of the former should be smooth, so that during the settlement of the latter the two will remain in close contact.

Water is said to abhor a right angle, as this increases the frictional resistance to its flow. Staunching walls should therefore be built at right angles to the walls from which they start, and long ones should have subsidiary staunching forks projecting at right angles from them. Intermediate between these may be shallow smooth vertical joggles in the masonry to increase the bond of the earth with it.

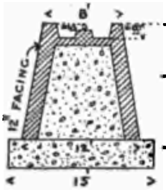
(*c*) *Staunching Forks.*—For cross-drainage works staunching forks projecting 4 to 6 feet from the wing walls should be built in the centre lines of the canal embankments when these are carried up to the abutments. They should be raised to at least 1 foot above canal full-supply level, and should have a top width of 2 feet and side and end batters of 1 in 8 and 1 in 4 respectively (Fig. 68, p. 294*a*). The inner top edge of the staunching fork is there shown starting from where the inner top edge of the canal bank meets the wing wall of the aqueduct. To secure more earth cover upstream to the staunching fork, it would have been better to have commenced it from the outer top edge of the bank.

(*d*) *Staunching Rings.*—Outlet culverts under earthen dams should be entirely surrounded at intervals by staunching rings; the one most upstream should be situated where it is not likely to be passed by a large amount of infiltration through the dam; the one most downstream should have the greatest projection into the dam, and should be constructed at its centre line (Fig. 37, p. 204).

FIG. 13

DAM CENTRAL WALL

SECTION



(*e*) *Design of Staunches.*—The abutting faces of all staunches should have a batter of at least 1 in 8 for low walls, and one of at least 1 in 18 for high walls, and the ends, minimum batters of about double these amounts. If the top of the staunch is narrow, it should be rounded off so as to prevent it from interfering with the settlement of the earth above it. If the top is wide, it should be formed with a key recess to prevent leakage across it (Fig. 13). The object of these arrangements is to ensure a solid junction between the masonry and earthwork during and after the final settlement of the latter.

The downstream faces of staunch walls embedded in earthwork and the portion of the outlet culvert downstream of the main staunching ring should be drained so as to get rid of excess water which might otherwise tend to soften the embankment there.

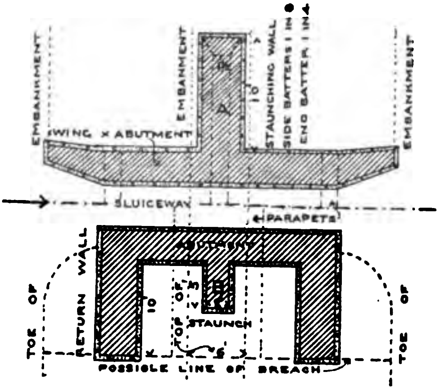
The efficiency of staunches is increased if the walls have a good cover of earthwork upstream of them, as this will retard the infiltration to them. Thus in Fig. 14, which is a plan of a sluice through a flood embankment, the long central staunching wall, A, is a superior arrangement to the side retaining walls, with a central staunch of less projection, B. The latter is not only more expensive than the former (as A in its central position may be of slight section), but is less effective, as flood water is thereby admitted nearer to the centre line of the bank, and is thus more likely to outflank the end of the upstream wall, and, if it does, to pass directly through the embankment beyond the short central staunch (which will thus be useless) and breach the bank.

FIG. 14

FLOOD EMBANKMENT SLUICE

HALF FOUNDATION PLANS

WITH STAUNCHING WALL



WITH RETURN WALLS

41. Subaqueous Cement Grouting.[1]

(*a*) *Rubble Grouting.*—The system of subaqueous cement grouting (or stock-ramming) was first devised by the late

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[1] Hanbury Brown's "Irrigation," pp. 157–164; Minutes of Proceedings, Inst.C.E., Vol. CLVIII., p. 1; Parker's "Control of Water," pp. 980–983.

Mr. W. R. Kinniple at the Hermitage Breakwater, Jersey, and was subsequently adopted for the repair of the Delta Barrage and construction of other barrages in Egypt. Shortly described, it consists in the injection under pressure of pure cement grout into the interstices of porous foundation material so as to fill them, and when set to convert that into a solid rich concrete. In the usual practice the site of the work is dredged out, and the foundation is formed by grouting large water-tight boxes filled with rubble, road metal and pebbles, which have comparatively large interstices. The process is costly in the expenditure of cement, but as a set-off in difficult works there are savings of time, staff and pumping charges which fully justify its adoption.

(*b*) *Principles of Rubble Grouting.*—The principles involved in this construction are—

(i) Cement grout will set in still water if formed with not more water than twice the bulk of the cement.

(ii) The green grout must not be subjected to having its cement washed out by the inflow of external water. Similarly, it should be delivered on to the work under construction in pipes passing through the overlying water.

(iii) The cement grout must be prevented from leaking away.

(iv) Cement grout (1 to 1), being twice as heavy as water, will, if properly applied, descend to the base of the work and gradually rise uniformly above it.

(v) The interstices of the material to be grouted must be sufficiently large to permit of the travel of the grout which is a viscid liquid.

(vi) The distance between the pipes down which the cement is poured under a pressure head must not exceed that which the grout can travel.

(vii) The scum rising to the surface of the grout, which consists of perished cement, must be cleared off, and not allowed to interpose itself above previously completed work, as thus it would form a porous layer.

(viii) Sand must not be mixed in the grout, as it would separate unequally from it when deposited, and would thus form friable porous planes.

(*c*) *Quicksand Grouting.*—When the Siswán superpassage on the Sirhind Canal, Punjab, was repaired, the natural sand was grouted by means of pipes, and much difficulty was experienced in getting the grout to flow through this fine material. A method of grouting in quicksand[1] has recently been patented in Germany. In this a pipe large enough to serve as a cement-injection tube is fitted at its lower end with an augur point and a helical screw blade. Just above this blade several holes are drilled in the wall of the pipe so as to discharge the grout outwardly over the upper surface of the blade. This boring apparatus is twisted down, if necessary by the help of a jet of water pumped through the pipe, and when it has reached the desired depth, grout is passed down the pipe, the drill is revolved backwards so as to withdraw it, and the grout flows out along the face of the blade. By the rotation the grout becomes mixed with the sand above, and the mixture is passed to the space below, where it builds up a cylindrical mass of cement mortar of a volume equal to that swept through by the blade. When the cylinder is completed to the required height, the drill is withdrawn and worked similarly alongside the first mass, and so on, so as to form the whole foundation required.

42. Springs.

Springs are met with in many foundations; in fact, in alluvial soil or sand, if the foundation bed is free from them, it is probable they exist below, and it will be desirable to deepen the excavation to disclose and deal with them. If a spring is not securely sealed, it may break through elsewhere, and give trouble in construction, or become a danger to the completed work. Each spring must be located and treated separately; this can be done by enclosing it in a ring of temporary masonry or a pipe 3 to 6 inches in diameter, inside which it is allowed to rise until it can be led outside the area in a pipe (Fig. 15). The permanent masonry is then advanced to the ring and allowed to set, the base of the area inside the ring is thereafter cleaned out, and, if the foundation is of sand, the bed is filled with ballast to prevent the sand rising. A perforated pipe is then placed centrally in the ring, so as to collect the spring water, the temporary masonry removed, and the whole vacant space filled with cement masonry or concrete;

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[1] *The Engineer*, Vol CXI., No. 2,881, dated March 17, 1911, p. 273.

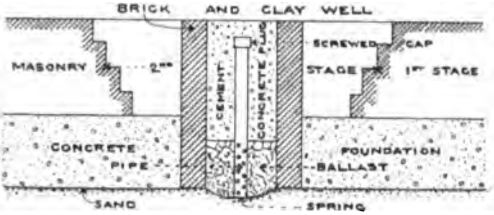
when this has set, the pipe is closed by a screwed cap. In difficult cases resort may be had to the method of subaqueous grouting (Art. 41). Springs in rock foundations can usually be dealt with by passing them through a pipe alone without other temporary arrangements. Weak springs in such foundations may be surrounded by empty cement casks, round which concrete or masonry is formed and allowed to set. The casks are then removed, and the spaces thus left are filled with cement masonry or concrete. In all cases the spring should be allowed to flow until the permanent work enclosing it is quite set.

When subsoil water is met with generally throughout an alluvial foundation it should be collected by shallow channels and led to sumps, from which it can be pumped, and the base of the foundation filling should be made quick-setting by the use of a liberal amount of cement. To meet contingencies the pumps should be able to deal with considerably more water than is anticipated.

FIG. 15

CLOSURE OF SPRING

SECTION



43. Construction Materials.

All ordinary materials which can stand the action of water, and are sound and durable, are suitable for the construction of irrigation works, and what is chiefly available in sufficient quantity in the neighbourhood can generally be utilised, otherwise the works might not be practicable on account of their cost.

Stone is better than brick, but in alluvial soils the latter is alone available in bulk—even there, however, parts liable to the action of considerable scour are best built of stone. Masonry dams and overfall weirs being on sound rock foundations, stone should be readily procurable for them; they are rarely, if ever, constructed in brickwork. Good stone and bricks are essentially permanent materials requiring little maintenance when exposed, and are safe from deterioration in the heart of a work.

Mortar used should invariably be hydraulic, or it will be washed out. Good hydraulic lime is sufficient for most irrigation work, and cement is required only where quick-setting or extra water-tightness is necessary.

Timber is a temporary material, and is therefore little used in India. In America it was originally employed extensively in the earlier irrigation works, and was there given a life of only fifteen years. In some countries it has the disadvantage of being liable to be destroyed by fires or insects, etc. It is therefore replaced by more permanent construction as the countries develop, and its use for the main part of structures can be justified only in backward, undeveloped lands where it itself is abundant and cheap. Timber is, however, most useful for temporary structures and for subsidiary works of construction. Only varieties which can stand being alternately wet and dry should be used.

Ironwork must also be considered a temporary material, and should be employed only where it can be examined periodically and kept in repair. It has to be used for sluices, and they should therefore be designed to permit of proper maintenance. It is also utilised successfully for piles, which, as they are buried, have a long life; and as they are usually outside foundations, can there be replaced when necessary. It does not seem advisable to construct the outlet culvert of an earthen dam of ironwork, although, of course, the segments of which it would be built up could be taken out when deteriorated, and new sound ones substituted for them. It would, however, be better to surround the metal ring with one of concrete, which material will suffice alone when the other has become unsound.

Ordinary concrete is a most useful material where the work is heavy in section. It can be made practically monolithic and water-tight by cheap labour and materials. Reinforced concrete has lately been used, but until longer experience has been gained of its durability in hydraulic construction, it would be better not to adopt it for important irrigation works.

Brickwork in alluvial soils is liable to be attacked by the rise of subsoil alkaline salts, which disintegrate ordinary well-burnt bricks and lime mortar. To prevent decay from this cause, the brickwork is often laid in cement mortar, an expensive and not perfect protection. It is best to use overburnt bricks, as these are able to withstand the action of the salts. Brickwork in the waterway of a canal is also preserved by the washing out of the salts, and it would therefore seem advisable occasionally to water thoroughly the superstructure above the waterway when the canal is flowing.

44. Utilisation of Water Power.

A large amount of water power can be furnished by certain kinds of irrigation works—storage reservoirs, overfall weirs and falls on large canals. Unfortunately, these are generally situated in places remote from manufacturing centres, and until recently this acted as a bar to their utilisation in India in this way. With the advent of hydro-electric installations for light and power, this difficulty has been met, and it is therefore advisable always to provide in such works sluices by which the water power can be made available when required. These can easily be fixed during the construction of the works, but only at extra trouble and expense subsequently. Water power has been utilised for some time past for milling, raising irrigation supplies to a higher level, etc., in highly developed countries such as France, Italy and Spain.

Another difficulty is that irrigation schemes have to be worked intermittently in the interests of cultivation, and it is only seldom that water can be allowed to run to waste to furnish power. To meet this in hydro-electric installations it is desirable to have steam power as a stand-by, or to provide subsidiary storage capacity below them to impound and utilise water which would otherwise have to be discharged for their exclusive benefit. A converse arrangement is to design the storage work for water power and to utilise the expended water for irrigation lower down. In this case, to act as a stand-by for the latter, a regulating or impounding reservoir is desirable upstream of the intake of the irrigation works.

The conditions required for a successful installation of water power are:

(i) An abundant and never-failing supply of water (either naturally available or obtainable at a cheap rate by storage).
(ii) A considerable and steep fall close by (to increase the capacity and lessen the cost of the generating works).
(iii) Proximity of the place where the power will be utilised (to reduce the expense of transmission); and
(iv) A steady and full demand for the power (so as to get the greatest return for the least outlay).

45. Measurement of Water—Modules.

(*a*) *General Remarks.*—In Article 26 (*c*) it was stated that in backward countries, and in ones where the available supply fluctuates greatly in amount, the system of assessment by the area of crop matured was generally the best; also, that in more highly-developed countries, with a more regular supply, the assessment was based on the quantity of water issued. The former system undoubtedly tends to cause an extravagant expenditure, which has to be controlled by authority, while the latter leads to economy which it is in the interest of the irrigator himself to practise.

The devices made to measure irrigation supplies are known as modules; a module should satisfy the following conditions:

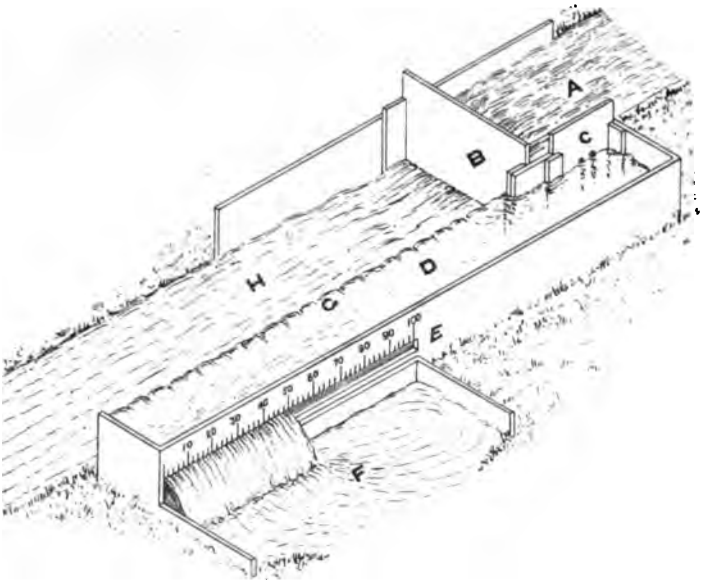
(i) The quantity delivered should be practically constant in amount, although the head in the supply channel varies;
(ii) The loss of head due to the measurement should be small;
(iii) The purchaser of the water should be able to see that his supply is correctly made;
(iv) The module should be cheap and simple, and if it cannot be made locally, should be repairable locally;
(v) It should work easily and not be liable to derangement by silt, rubbish, etc., i.e. it should serve equally well for turbid as for clear water;
(vi) It should be secure against being tampered with fraudulently.

Modules have recently been invented and installed in India with satisfactory results, but more extended use is necessary to establish their suitability. Many forms, some very elaborate with clockwork, are used in America. A perfect module has, however, still to be produced, as it is not so easy to design an accurate means of measurement for an open irrigation channel as it is a meter for a clear pipe supply under pressure.

(*b*) *The Foote Module.*—A simple and cheap module,[1] designed by Mr. A. D. Foote, M.Am.Soc.C.E., which can be constructed by a carpenter, is sketched in Fig. 15A.

FIG. 15A

FOOTE MODULE



A is the supply channel across which is a shutter, B, which forces the discharge to be measured through a sluice, C, into a box, D, from which it passes through a graduated and adjustable opening, E, into the distributary channel, F, while the excess water entering D flows over the spill-board, G, of that box back into H, the tail of A. If D is made long enough, and the edge of G sharp enough, nearly all the excess water admitted into D will spill over to H, and the head on and discharge through E will be practically constant. The loss of head is only an inch or two.

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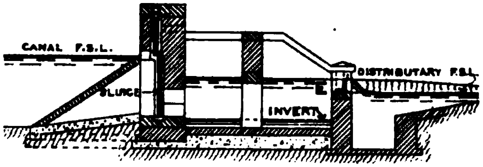
[1] Transactions of the American Society of Civil Engineers, Vol. XVI., 1887.

(*c*) *Spanish Module.*—Figure 15B shows a module constructed in Spain.[1] The water in the distributary, A, which is to be measured, flows into the module through an opening in the headwall, B, that is controlled by a sluice, into the chamber, C, and thence through narrow slits into the chamber, D, where it arrives stilled and without perceptible velocity. Finally, it passes out of the module over the knife-edged iron weir, E, upstream of which is fixed a reference gauge, with its zero at weir crest level.

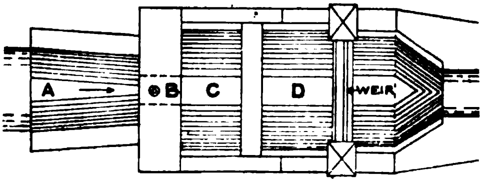
FIG. 15B

SPANISH MODULE

CROSS SECTION



PLAN



Both these forms of module take advantage of the well-known hydrostatic principle of flow through a succession of chambers. If there are two such chambers having a sluice of area A_1 with a head H_1 on it in the division wall, and a sluice of area A_2 with a head of H_2 on it in the tail wall, then $\frac{H_2}{H_1}=\frac{A_1^2}{A_2^2}$ and thus the ratio of the heads as the water levels fluctuate is constant. If A_2 is made larger than A_1, H_2 will always be smaller than H_1, and the fluctuations of H_2 will be much smaller than those of H_1.

(*d*) *Other Forms.*—Other old forms of module are those in which a float in the outlet chamber controls the discharge of a sluice in the inlet chamber; a float in a single chamber is mounted on an equilibrium inlet and outlet valve, and controls its discharge; a hollow float with inlet orifices connected to a vertical discharge pipe passing through a water-tight joint packing in a horizontal diaphragm, dividing the inlet from the outlet chamber; floating siphons with inlets in a chamber and discharging through their longer limbs outside it; and a float with a plug of peculiar form suspended from it giving a constant discharge through an orifice through which it itself passes. There are objections to all of these, chiefly the loss of head occasioned and the liability to derangement.

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[1] Minutes of Proceedings, Inst.C.E., Vol. XXVII.; "Irrigation in Spain," by George Higgin.

When a branch channel taking off from a canal is entitled to a fixed proportion of the supply, a simple arrangement is to construct across them regulator notches of widths in that proportion, but otherwise precisely similar. The approach channels to the regulators should bifurcate at the same angle from the canal upstream (see Fig. 120, p. 486, for a similar arrangement). On distributaries with regulated supply the different irrigators should get their individual supplies during fixed times.

46. Needles, Baulks, and Gates.

On alluvial canals the openings of regulators are usually controlled by wooden needles, baulks or gates; each form has certain advantages and disadvantages.

(*a*) *Needles.*—In Sind these are of teak, and are generally 4 inches by 4 inches in cross section; in Egypt they are of pine, and are about 10 inches by 6 inches. The section should be varied in accordance with the length and weight of the needles, the water pressure against which they have to be worked and the means of operating them. They are placed vertically side by side across the opening to be regulated and as close as possible to each other, but there is much leakage between them, especially if they have warped. In Egypt, to increase their staunchness, needles were made with bevelled edges, but this design has been abandoned there.

The needles are supported by horizontal wales placed across the controlled opening; formerly in Sind these were teak beams, but on account of their large cross-sectional area blocking the waterway and liability to warp and perish, such beams are now superseded by rolled steel joists. The wales are spaced apart at distances calculated to allow each to

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support an equal amount of water pressure, and thus to be of the same section. They are let down in grooves in the masonry sides of the openings, and are supported therein by vertical wooden distance pieces fitted into the grooves. They can thus easily be taken out when that is necessary for painting, etc.

The regulation of supply is effected by inserting or removing needles as required, that is, by forcing them down or levering them up. Thus the unblocked area is representative of the whole waterway of the canal head itself, and bed silt and clear top water are both passed through it. This is of advantage in preserving a channel to a head regulator, and in distributing silt fairly between a canal and a branch from it. The only other advantages of needles are that they are cheap and simple. Their disadvantages are that they are not water-tight, so that they can be used only where water is plentiful, and some of it can be allowed to run to waste; moreover, their operation is slow and difficult, especially as the closure of the opening proceeds, and they are liable to be broken when being forced down. Some of the older weirs have their undersluices closed by needles, but gates or quick-acting shutters are fixed in modern ones.

(*b*) *Baulks* (Fig. 15c).—These are horizontal, regulating beams spanning the waterway and having their ends inserted in vertical grooves in the side masonry. To close the opening they are lowered one after the other so that an upper one rests flush on a lower one. Although the joints are not quite water-tight, being fewer than those of needles, and the lower ones being weighted by the upper baulks, much less water passes through them than through needles. Originally the baulks were of timber, but recently they have been made of rolled steel H beams with teak packings bolted to the horizontal webs so as to form solid flitched beams. The former kind are difficult to get down, but the latter descend easily by their own weight. For the wooden baulks the best arrangement is to have hooks fixed to iron straps round their ends inside the masonry grooves, so as to be out of the rush of water. These hooks can be caught by rods with eyes, and thus lifted by men. The iron baulks near their ends have handles riveted to the webs, and below them the teak packing is cut away, so that the baulks rest flush on each other. The baulks are raised by chains and differential pulleys mounted on wheeled runners or travellers, moving on light steel rolled beams fixed across heavy steel rolled beams spanning the opening, of which the upstream one is placed just upstream of the groove for the baulks.

Baulks, besides being more water-tight than needles, are stronger, can be handled more quickly and easily, and can be utilised as " rising sills " (Art. 219 (*d*)). The water passing over them in a thin film acts less violently on the canal than is the case when needles or gates are used. The objections to them are that, as they obstruct the flow of the bottom water heavily charged with silt, they cause the approach channel to the regulator to be silted up, and they cannot be operated with sufficient quickness to keep pace with rapid fluctuations of the river.

(*c*) *Gates.*—For small spans up to 5 or 6 feet gates of wood or iron are usually fitted with mild steel lifting rods, each passing through a capstan head fixed to a platform, that is itself carried by jack arching springing from the piers, which for this purpose are prolonged in plan upstream of the sluice vent. For larger spans horizontal shutters of built-up ironwork are used, and are lifted by chains worked by winches travelling on rails on overhead girders. To close the gates it may be necessary to force them down by ramming them with spars.

If the vent to be closed is of considerable height, the gates and shutters for easy manipulation and for being lifted above full-supply level are in two or three parts of heights adjusted so as to secure equal water pressure against each. Each part travels up and down in its own groove (which may be formed in the side masonry, but is better made of cast iron), and has a stop at the bottom to limit the descent of the gate. The grooves are parallel and as close as possible to each other, and are arranged so that the lower gate is upstream, and the upper one downstream. To make the meeting junction of the gates water-tight a horizontal wooden staunching batten can be there inserted between them (Fig. 116, p. 472). For spans of 20 feet and over the shutters should be on the Stoney system bearing on series of rollers mounted in hanging frames, which greatly reduce the friction of their movement. The faster the action of the individual gates and of the entire series of them, the better, so that more rapid regulation may be effected, especially when the river level fluctuates quickly. Travelling winches passing from one span to another so as to work the gates thereof consecutively have thus slower action than the arrangement shown in Fig. 118 (p. 474*a*). There a quick-acting, worm-geared headstock is placed in each span so as to raise or lower each of the two gates independently of the other. The headstock is placed between each pair of gates, and is connected to drum shafts through spur gearing, thus giving double purchase of spur and worm gearing when opening. (See also Art. 219 (*g*) (ii).)

Multiple gates are in fact enlarged baulks, but are superior to them in being more water-tight and being more easily and quickly worked, the different sections, simultaneously, if necessary; they also can be used as rising sills.

(*d*) *General Remarks.*—Although these three forms of regulating apparatus do not increase the total amount of heavy silt in the canal, which is the amount originally held in suspension by the admitted water, they affect the place of its deposit, causing the bulk of the sediment to be precipitated upstream, and thus tend to block the entrance to the canal. To prevent such blocking from cutting off supply, it is necessary that at intervals the obstruction to flow should be removed so that the deposited silt may be carried down the canal, and its depth thereby diminished. Needles cause the least original obstruction to bottom silt, but, as they can be worked only slowly, the deposit upstream of them may eventually be as great as that above the other forms. To get rid of the admitted silt it is advisable to have escapes and scouring sluices downstream of the regulator (Art. 205 (*e*)). Of the three forms the order of increasing efficiency is needles, baulks and gates, and that of increasing cost is the same. Needles are best for branch canal regulators, baulks for head regulators with small spans where there is not much bed silt to contend with, and gates for those with large spans and where the river may have a rapidly fluctuating level and may carry much bed silt.

47. Irrigation Plantations.

(*a*) *General Remarks.*—Plantation work is noticed here, as it can and should be carried out on all descriptions of irrigation works. Thereby the scenic beauty of the works is enhanced; shade is given which is always grateful in a tropical country; revenue may be produced which will be an offset to expenditure on the general establishment; and a test of the frequency of inspection by those in charge will be afforded, as plantations to be successful cannot be looked after spasmodically, but must receive constant attention, and, while that is being given to them, the works themselves must also benefit. The larger operations of afforestation of catchment areas will naturally be carried out by a Forest Department, and not by engineers, but the latter are immediately interested in them. Although the old idea that forests can create rainfall is now generally abandoned, as it is recognised that precipitation depends upon aerial currents moisture-laden after their passage over immense ocean areas, still forests greatly benefit irrigation in the following respects:

They tend to attract and precipitate rain which might otherwise pass over the area if that were unforested; this can be utilised in replenishing reservoirs and in watering the irrigated area.

They lessen the evaporation of the ground, and cover that with absorbent humus, thus prolonging stream flow in the fair season.

They tend to mitigate the violence of storms.

They thus reduce the intensity of high floods and diminish the amount of silt and *débris* borne down by these.

Irrigation plantation work naturally varies according to the locality and climate, but the main principles on which it should be conducted can be applied after taking local conditions into account. The following remarks are therefore of a general character. Whenever possible, it is of course advisable for the engineer to avail himself of the advice of a forestry expert; where this cannot be had, it should not, however, be difficult for him to establish and maintain plantations on his works.

Other remarks on roadside plantations are made in Article 312; some of these apply also to canal plantations.

(*b*) *Classification of Plantation Trees.*—Trees in irrigation limits may thus be classed according to the objects they serve:

(i) Shade trees are those which are primarily planted to give protection from the sun near irrigation buildings, or to form camping grounds. Naturally, all trees give some shade, but the other classes have additional utility.

(ii) Timber trees are those which principally furnish wood useful for constructional purposes, including fuel therefor. Except for minor produce they do not give annual revenue, and thus are not of financial benefit until they are felled, when of course a blank is caused in the plantation. They may usefully be grown on the margins of reservoirs, on waste lands commanded by irrigation, in advance of more valuable canal plantations, and near inundation embankments, to provide material for emergent repairs. Large areas thus planted would have a considerable economic value, and it is highly desirable that they should thus be utilised. In India the babhul (*Acacia Arabica*) is generally the best tree for such plantation.

(iii) Revenue trees are those that bear fruit, seeds, etc., which have a marketable value, and thus produce annual revenue without the necessity of their being felled. They are therefore the most remunerative of all three classes, and, wherever practicable, should be planted. To secure better supervision and to facilitate watching they should be in compact areas. To obtain the greatest amount of revenue they should be grown near to markets where their produce can be sold; in remote situations trees of which the fruit has a ready local sale should be established. If, however, there is a railway near, the best varieties of grafted trees should be cultivated so that the largest towns may be supplied with fine fruit, and the advantage of irrigation in growing it may thus be utilised.

(*c*) *Varieties of Trees.*—The kinds of trees to be planted are such as will flourish in the soil and climate of the locality. The best guide to follow is that given by trees already growing in the neighbourhood or under similar conditions elsewhere; experiments can, however, be made with other varieties. Along river embankments and near masonry works trees with wide-spreading roots should never be planted. On compact areas plantations of the same kind should be established. As long lengths of avenue of the same class of tree are monotonous, the kinds of trees planted in them should be varied. Trees which are likely to decay soon, or, being shallow-rooted, to be blown down, should not be planted. Fruit-producing bush plants and trees which do not attain a fair height should not be grown on canals, but may be cultivated elsewhere.

(*d*) *Spacing of Trees.*—This should be regulated by the final spread of the branches of the trees, so that the ends of these may not quite touch each other and thus interfere with growth. As trees take a long time to mature, plantations thus set out will at first be thin, as they will not then fully occupy the ground; the original spacing may therefore be half the final one, and as the young trees develop, the alternate ones can be removed. Along river embankments trees should not be planted nearer than 10 feet from the river toe, nor than 20 feet from the inland toe. Along new canals they should not be planted unless the land margins are at least 20 feet wide on each side; when these are of this or greater width the trees may be planted along each bank, but not within 10 feet of the edge of the canal, so that their roots may not block it. On the inspection path side the line of trees should be outside the path in order that the view of the canal therefrom may not be obstructed. If there are trees on old canals with narrower land margins which are not injuring the canal nor neighbouring land, others of similar nature and at similar spacing may be grown in avenue blanks. Trees should never be planted within 30 feet of a masonry work, so that their roots may not injure it nor form leakage planes near it.

Where the two lines of an avenue are close together, the trees in each may be spaced midway between those on the other side; where such lines are far apart, the trees should be grown opposite to each other.

(*e*) *Nurseries and Seedlings.*—Ordinary trees will flourish best if grown from seed planted *in situ*, but in the tropics the attendant cost of subsequent protection and watering renders this form of sowing prohibitive, except in areas where the plantation is compact. For canal plantations seedlings should be raised in nurseries (in flower pots, old tins, special baskets, etc., or in seed beds), and these should be formed near the future plantation, where water can be easily obtained and at quarters where staff is maintained and can look after them. The seeds should be sown as early as possible in the proper season, so as to take full advantage of it. They should not be forced to grow too rapidly by excessive watering; if they become too weak to stand by themselves, they should be cut back. Small cuttings of certain trees can also be raised in nurseries, but as a rule they do not produce such fine trees as those grown from seed.

On concentrated areas fruit-tree seeds can be sown at intervals on small mounds formed by digging and scraping up the soil in parallel lines spaced the proper final distance apart. Seeds of timber trees can be sown broadcast on ploughed-up land or thickly along ridges formed by a furrow on each side, each pair being properly spaced from 10 to 30 feet apart, and the seedlings thinned out as necessary.

(*f*) *Planting Out.*—Seedlings should be planted out in their final positions at the beginning of the rainy season, when they are about 2 feet high, provided water is available for regular watering; care should be taken that their roots are not injured in the process. On soft ground only small tree holes are required, but on hard soils larger ones (Art. 312 (*d*)) should be excavated to give the seedlings a good start and lessen future maintenance charges. Tree holes should be square in plan, so that the roots of the seedlings will be induced to enter the natural ground at the corners. If the holes are circular in plan, the seedlings may become "pot-bound," i.e. the roots may follow the circumference and not penetrate the subsoil.

A concentrated plantation should be surrounded by a good fence; on canals a fence 6 feet in diameter and 3½ feet high is required for each tree to protect it from injury. Fences should be cheap, strong and protective; they are usually made of dry thorn, but live hedges are also formed; the latter should be grown in advance ready to receive the seedlings. All fences and hedges should be kept clear of the seedlings, so as thus not to dominate and deflect them.

(*g*) *Watering.*—The proper intervals between waterings of planted-out seedlings depend upon the species of the tree, the amount of water given, the nature of the soil, and the dryness and heat of the locality; they should be neither in excess nor in defect. Each watering should be a full one, so that as much water as possible may soak into the ground. Surface waterings are objectionable; they are expensive, as a large portion of the water is evaporated, and they tend to puddle the surface and keep only it moist, so that the root fibrils are not encouraged to penetrate deeply, and may thus perish if there is any lengthy interruption between the waterings (see Art. 312 (*d*)). In concentrated areas under command small field channels should be led along the lines of the tree seedlings to give them water.

After each watering the surface soil should be stirred up so as to allow it to become aerated, and so that its loose texture may protect the ground below from desiccation. Waterings should not be stopped until the roots of the seedlings have reached the plane of permanent subsoil moisture. The time thus taken will vary according to the nature of the soil and the extent of its natural saturation, and according to the rate of growth of the trees. As a rough rule it may be said that the watering should be prolonged until the seedling is from 3 to 5 feet high, and should thereafter be continued until the next rainy season is well established, so that the seedlings during that season may become accustomed to natural conditions. Should a tree show that it is suffering from the stoppage of artificial watering, that must naturally be renewed during the current dry season.

(*h*) *General Maintenance.*—The enclosures of seedlings should be kept free from grass, the earth surface well loosened and mulched or manured (canal silt and weed clearances are suitable for the purpose), and the fences trimmed. Although stable manure is itself expensive, it is economical to use it, for, as it accelerates the growth of the young trees, it diminishes the period during which they require to be watered, etc.

Care should be taken that the seedlings are well started, so that they may grow straight, regularly and symmetrically. To ensure this they should be trimmed as necessary, and all overhanging branches, etc., which dominate them and will thus deflect them should be removed. They should be protected from frost by covering them lightly with dry grass, etc., during winter.

Where inferior trees are growing too near superior ones, and interfering with their development, the former should be felled. Similarly, trees growing too close to each other should be thinned out, and those which have more than one stem should have the inferior ones removed. This is a work which requires judgment (as errors cannot be corrected), and should therefore be entrusted only to experienced men.

Branches which have to be lopped should be cut off close to the trunk or main branch, so that the bark may grow over the cut ends, which should be neatly sawn or adzed off and tarred, to prevent decay from starting.

Trees which are felled because of their decay should be replaced by those of another kind, to prevent their similar failure and the exhaustion of the soil. Branches and trees which fall, or are likely to fall, or which obstruct flow or inspection, should be removed, and the stumps left should be rooted out or burned. All fellings should be sold, or burned if there are not buyers. An untidy avenue is an eyesore, and the fellings if allowed to remain may attract injurious animals, insects, etc., or cause germs to grow which may damage the live trees.

The works establishment should continually extend the plantation in their spare time, as well as maintain the existing one properly, and may be encouraged to interest themselves in this work by small rewards.

CHAPTER III.

RAINFALL, RIVER DISCHARGE, AND SUPPLY.

48. Rainfall.

(*a*) *Natural Disposal of Rainfall.*—When rain falls on a catchment, part of it is evaporated from the surface of the ground and vegetation, part of it penetrates more deeply and reappears in streams as springs or seepage, and part of it "runs off" the surface to produce flood flow. The yield from springs and seepage is generally large in the temperate zones and small in the tropics, while that of flood flow is the reverse. The loss of rainfall in regard to stream discharge is thus practically due to evaporation alone (direct or indirect), as the great bulk of absorbed water is generally returned by springs. This loss is greatest where the rainfall is of light intensity and is prolonged, and the drainage area is flat and absorbent; it is least when the conditions are the reverse.

(*b*) *Utilisation of Rainfall.*—Rainfall is utilised for irrigation either directly from that precipitated on the irrigated area, or indirectly from that falling outside such area and producing stream flow (which is led either directly into the canal system by a diversion weir or pumps, or indirectly into it after the flow has been impounded in a storage reservoir), or from that saturating the ground which is made available by wells. Thus rainfall, including snowfall and dew, is the source of all water supply for irrigation.

(*c*) *Utility of Rain.*—Rain falling on the irrigated area is particularly useful, as it is delivered without any loss or labour, is free from injurious salts, is charged with air, including beneficial gases. and has usually a higher temperature than water artificially applied. The disadvantages attending it are that it is beyond human control, and, in the tropics especially, is extremely variable in intensity, amount and periodicity; it is to remedy these that artificial irrigation is there practised.

Further, rainfall being practically pure, crops grown under it exhaust the soil, and this has to be enriched by the application of manure. In recording such rainfall it is particularly desirable to note if the individual showers are advantageous or the reverse to cultivation. Rainfall should be utilised as much as possible so as to economise the draw-off from storage, e.g. rice cultivation should be started as soon as practicable in the proper season without waiting for the filling of the reservoirs which are required to supplement the rain.

(*d*) *Rainfall Statistics.*—Although rainfall outside the cultivated area is the source of supply of irrigation water, its total amount is not the sole factor to be depended upon, as only a portion of it can be made available, and that portion is determined by other factors (Art. 50, p. 98). Thus it cannot be too clearly stated that rainfall statistics by themselves do not form a safe guide in determining the amount of supply probable. The utility of such statistics is that they are more numerous than other hydraulic records, and that by an intelligent application of them estimates of such supply can be made with some approximation to what may fairly be expected. To render the approximation close, the other factors must be taken properly into account, and, wherever possible, similar conditions should be dealt with.

(*e*) *Annual Variation of Rainfall.*—Despite the annual variations of rainfall, when long periods are considered the mean rainfall does not vary greatly, and meteorologists believe that the fall takes place in cycles of about thirty-five years, and that the average annual fall of such cycles does not vary by more than 2 per cent. Another observed fact is that the rate of fluctuation of the total rainfall of the one, two and three consecutive wettest and driest years during the series considered is practically constant in each case for all localities. In some countries, e.g. South Africa, it is believed that the rainfall is gradually decreasing. Rainfall is due primarily to evaporation by the sun from the surface of large water areas. Any variation of the rainfall of the whole world will thus be due to a variation of solar radiation, and any general decrease of rainfall is therefore not likely to take place in short historic periods.

The time during which rainfall has been systematically observed is, however, comparatively short, and these beliefs may be altered when the record becomes longer. Anyhow, it is not safe to depend upon the observations of only a few years' duration when an irrigation scheme is under contemplation. Also, observations on works in operation should be continued as long as possible so as to obtain a prolonged record for them and for comparison with new projects under similar physical conditions, but having only a short rainfall record. The annual variation of the rainfall is so considerable that the average rainfall of a series of years cannot be assumed to be the amount which may be precipitated in any one year. What should be taken into account is the worst rainfall condition which has to be met by the works concerned.

(*f*) *Local Variation of Rainfall.*—Not only does the rainfall vary from year to year at the same place, but also from place to place during the same year. The general variation of rainfall does not depend entirely on latitude, but also on local conditions, such as the altitude of the land, the distance from the sea, the nearness to mountainous areas, and the character and direction of the prevailing winds. Such variation may be very great, and it is said to increase as the size of the tract considered is diminished. This dictum, however, requires some interpretation, as each rain-gauge of course records only the rain falling on its own neighbourhood, the area of which is practically the same for all instruments. What is meant is that the larger the area of country with the same general physical features and characteristics, the less will the precipitation on it differ at neighbouring points, and therefore the fewer need be the rain-gauges established in proportion to its size to determine the average fall on it. Conversely, when the physical conditions vary considerably, the greater should be the number of rain-gauges. In English waterworks schemes an average distribution is one rain-gauge to 1,000 acres; for the great plains of Northern India it has been proposed to vary the number of observation stations gradually from 1 for areas of 50 square miles and less to 6 for those extending from 500 to 750 square miles. This latter distribution would be quite insufficient near the Western Ghâts, where the rainfall close to the crest may be double what it is 3 to 5 miles, and quadruple that 30 miles to the east. The number of stations should be determined from a meteorological point of view by reference to the surface physical features of the area under examination (see Art. 103 (*b*)), and from an irrigation one, with respect to the general natural conditions

(Art. 50), so that an idea may be obtained of the amount of water likely to be available for the scheme concerned.

(*g*) *Effect of Altitude on Rainfall.*—As a rule rainfall increases with the altitude, but generally for accessibility rain-gauges are established on low ground. To multiply the number fixed in the valleys at the expense of those placed on the hills may thus lead to an unduly small estimate of the average rainfall. The proper way is to regulate the number of the former in due proportion to that of the latter. Generally it is not on the windward but on the sheltered or leeward side of a mountain chain that the heaviest rainfall occurs. This may be due to the cooling of the moisture-laden current by the former, and to the precipitation being carried onward to the latter by the wind.

(*h*) *Determination of the True Average Rainfall.*—The average rainfall on an area is often considered to be the arithmetical mean of the fall registered by the different gauges. This is correct only when each of the gauges records the average fall on an area of equal extent. The proper way is to determine first what is the area for which each gauge represents the average fall, then to multiply the fall registered by each by its represented area, and, finally, to divide the sum by the total area.

(*i*) *Estimate of Yield based on Rainfall.*—The effect of rainfall in producing discharge or "run-off" is largely influenced by the state of the ground, whether dry, damp, or wet when the fall commenced, and this fact should always be borne in mind when estimating the run-off likely to result from the rainfall. In the tropics, in regard to storage replenishment calculations that are based solely on the rainfall, falls of rain each less than 1 inch which occur when the ground is dry may be neglected, as practically all of this precipitation will be absorbed, and will not produce any sensible amount of discharge. Similarly, to get average results abnormal falls should be excluded. Such calculations may be made by considering separately each downpour likely to produce run-off and applying the proper coefficient of run-off to it, or, less accurately, by taking into account only the total of the falls each above 1 inch and a general coefficient. It must, however, be remembered that these estimates are but approximations, and they should be resorted to only in the absence of actual discharge observations. On no account should the total annual, or even the monsoon, fall multiplied by an average coefficient of run-off be taken as the basis of an estimate of the yield of the rainfall.

49. Rain-Gauges.

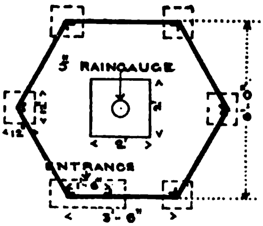
(*a*) *Observation and Location of Gauges.*—The observations of rainfall by meteorologists are carried out to obtain information useful for the country generally; those by irrigation observers are made to determine the relation of the precipitation to stream flow and the utility of the showers for cultivation. The proper distribution of the rain-gauges so as to ensure fairly correct estimates of discharge has been noticed in Article 48 (*f*). Before and during the construction of a work, when observers and supervisors are available, the rain-gauges should be numerous; their number can be reduced thereafter when knowledge has been gained of the relative falls at each, and of the extent of the constituent sub-catchments of which they are respectively representative.

To avoid eddies of air which might influence the amount of rainfall registered, the rain-gauge should, whenever practicable, be placed on level, open ground where there are not any obstructions, such as trees, buildings, etc., within 90 feet of it. There should not be any hills, steep slopes, valleys or large depressions within a quarter of a mile of a gauge intended to register the rainfall on plain country. Similarly, if the gauge is protected against damage by trespass by an enclosure, that should not form a solid obstruction to the rain currents, as, however, it often does. A suitable and cheap wire fence enclosure is sketched in Fig. 16.

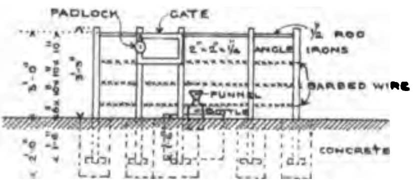
FIG. 16

RAINGAUGE ENCLOSURE

PLAN



ELEVATION



(*b*) *The Gauge.*—The rim of the gauge must be fixed securely and perfectly level, and must be preserved intact, as the accuracy of the collection of the rainfall depends upon the exactness of the area assumed to be contained by the rim. It is said that the amount of rainfall gauged decreases 1 per cent. for every additional foot of elevation up to 9 feet above the ground. This diminution is considered to be due to the higher velocity of the wind at the greater elevation, which carries some of the raindrops past the gauge. It is also held to be due to the parabolic path of the raindrops during wind, so that the area of the level rim of the gauge is only normal thereto if placed near the ground. Another reason may be that the lowest strata of the air are saturated by the splashing of the rain falling on the surface of the ground; drops passing through them thus increase in size, and when impounded by the gauge, consequently magnify the actual rainfall. This effect of splashing is visible when heavy rain falls on a hard, bare surface. The rim of the gauge is usually placed 1 foot above the ground, but for the above reason an elevation of 4 feet would appear more correct, and it would also practically obviate interference with air currents by the enclosure of the gauge, which would be at a lower level.

(*c*) *The Measure Glass.*—When the measure glass is read it should be placed perfectly level, and the readings taken from the centre of the " meniscus," or water-surface line, with the eye level with it. Should the glass be broken, another should be procured as early as possible, and, until it is received, the rainfall collected in the gauge should each day be separately placed in a corked and dated bottle for subsequent measurement. The measurements should be taken daily at the same time, and, to avoid confusion, should be recorded to show the fall in inches to two decimals, thus—0·03, 0·30 and 3·00. When there has not been any fall, the entry should be 0·00, indicating that a *nil* observation has been made.

(*d*) *Wind.*—The *direction* of the wind should be entered as from—N., N.E., E., S.E., S., S.W., W., or N.W. The *force* of the wind should be noted by numbers in accordance with a standard scale, such as is given on p. 98.

(*e*) *Automatic Rain-Gauges.*—The above remarks apply chiefly to ordinary gauges, for which an observer is required to measure the rainfall. Automatic rain-gauges record the rainfall for periods of a week to a fortnight by means of a paper diagram fixed to a drum revolved by clockwork, and traced thereon by an ink pen. The advantages of these gauges are that they—

(i) Measure the intensity, or rate of fall, of the rain as well as its amount;
(ii) Require less staff to observe them;
(iii) Can be fixed at out-of-the-way places representative of rainfall on hills, etc.;
(iv) Are useful as a check on ordinary gauge observations.

Their disadvantages are that they are expensive and may get out of order, e.g. the clockwork may stop or the ink pen may become dry, when it will not mark the diagram.

SCALE FOR FORCE OF WIND.

Number.	Designation.	Description.
0	Calm, or light	No visible motion of leaves; smoke rises vertically, or nearly so.
1	Gentle breeze ..	Moves leaves of trees.
2	Breeze	Blows up dust; moves small branches of trees.
3	Strong breeze ..	Sways ordinary trees.
4	Gale..	Sways large trees; breaks small branches.
5	Hurricane ..	Prostrates trees and buildings.

50. Yield from a Catchment.

(*a*) *Factors influencing the Amount of Yield.*—The total amount of water which runs off the surface owing to the fall of rain on it is known as the "yield" of the catchment concerned. The yield from a catchment depends upon—

(i) Its size.
(ii) The nature of the surface; whether hilly, sloping or flat; barren, grass-clad or cultivated; treeless or wooded; impermeable or permeable; wet or dry; free from or containing minor reservoirs or swamps.
(iii) The extent, intensity and frequency of the heavy falls of rain, which in the tropics produce

practically all the run-off; and the position of the area with respect to the direction of reservoir-filling storms.

The behaviour of each catchment has to be studied with respect to these natural conditions, which on account of their variety may make it differ from that of others unless they have similar physical characteristics.

It will be noticed that, although the yield depends primarily upon the rainfall, its amount is influenced greatly by the features of the catchment described in (ii) above. Those mentioned first in each clause tend to produce violent short-lived discharges, and those subsequently, gentler and more prolonged flow. In the tropics the yield is almost entirely due to heavy rainfall, and the rate of "run-off," or surface discharge flow, diminishes rapidly on the cessation of the rain; in the temperate zones much of the yield is produced as seepage, which enters the rivers for several days after the rain has fallen. It is thus easier to calculate the yield of particular downpours in the former than it is in the latter.

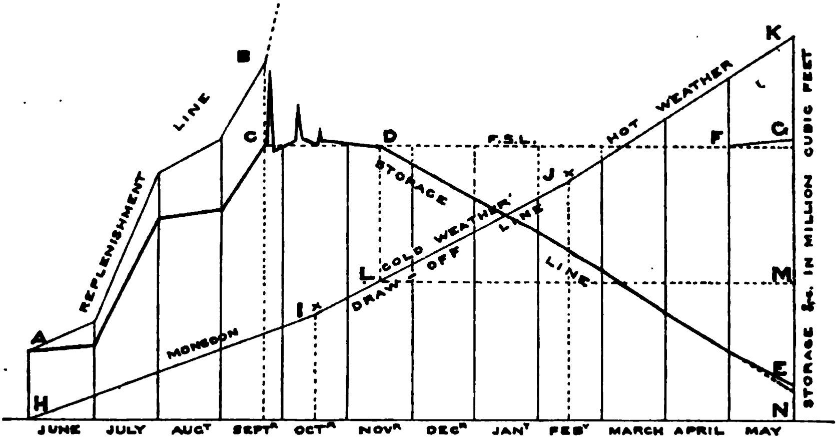
(*b*) *Determination of Sufficiency of Catchment.*—The proper replenishment of a reservoir must be assured in ordinary bad years, as well as in good ones, by determining its capacity with reference to its catchment area and the probable yield therefrom. In years of famine, however, the run-off from catchment areas in a country stricken with drought, however large, will be very small. Fortunately, there are many more years of deficient rainfall than ones of total scarcity, and it is during the former that a reservoir having a generally sufficient catchment will be of substantial benefit to the country, and will justify its cost.

To determine the sufficiency of the yield on the above basis during a series of years, the estimated replenishment, draw-off (including all losses, water run to waste and consumption), and net storage during each month should be entered in tabular form after assuming a full-storage capacity for the contemplated reservoir. If the net storage at the end of the dry weather is generally a *minus* figure, the full storage capacity should be increased accordingly, provided the calculated yield shows this will be justified; if it will not, the draw-off, i.e. the irrigating capacity of the work, should be reduced as shown to be necessary. If, however, that final net storage is generally a large *plus* figure, the irrigating capacity should be increased if the area under command allows of this. From the table a diagram showing the net storage at the end of each month can be plotted (Fig. 17).[1]

In this diagram the ordinates represent the calculated replenishment, draw-off (including all losses and consumption), and balance storage in million cubic feet at the end of each month, and the abscissae the months themselves. The replenishment line, AB, and the draw-off line, HIJK, are first plotted, and the storage line, ACDE, is deduced from them, its ordinates being equal to the difference between those of the other lines. The line AB and the portion AC represent what took place when the reservoir was filling until it first attained full-supply level; the portion CD extends for the period from when the waste weir first came into play until it ceased to flow; and the portion DE indicates the storage capacities during the rest of the year. To enable this last portion to be plotted, horizontal lines are drawn through D and L (where the vertical through D cuts the line HIJK), and the storage ordinates from DFG are made equal to the

FIG. 17

STORAGE DIAGRAM



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[1] See also Minutes of Proceedings. Inst.C.E., Vol. LXXI., p. 270, and "Public Water Supplies," by Turneaure and Russell, first edition, p. 313.

draw-off ones from LM. FG represents a small increment of storage due to hot-weather storms. If the reservoir does not fill, the point D for its diagram would be that of the highest storage capacity attained. If it is desired to ascertain the amount of the yield run to waste over the waste weir, the line AB would have to be extended to D^1 vertically above D, and DD^1 (less the draw-off during the period concerned) would represent that amount, and would indicate by how much the full-supply storage could be increased by enlarging the reservoir. To establish the proper amount of enlargement the diagrams of several representative years, and not only that of a single one, would, of course, have to be considered.

51. River Discharge.

As noted in Article 48 (*d*), estimates of the yield from observations of rainfall alone are but approximations; they should be made only when statistics of actual river discharge are not available. Before an important scheme is commenced, there should be a record of the discharge for at least ten years; but if the stream gaugings extend only for a shorter period, they should be supplemented for the deficient years by calculations based on the rainfall and checked by comparison of the two sets of rainfall and discharge observations during the time both were being carried on simultaneously. A still better comparison of the rainfall on and discharge from the catchment of a scheme under contemplation when the record of the latter is a short one can be made by taking into account the relative results of the catchment of a neighbouring completed work with longer statistics of both kinds of observation. For this purpose the two areas should be physically alike, and the rainfall on them of similar amount and character.

Rain- and river-gauges should be established as soon as the investigation of a project is determined on. The observations of discharge, if correctly made, will directly show what is the actual yield of the catchment; from those of rainfall only an estimate of that yield can be made by taking into account the probable effect of all the factors noted in Article 50 (*a*) which influence the amount of run-off.

If a river is subject to sudden alterations of its volume, it is obvious that gaugings carried out only once or twice a day will not register its true discharge. If, however, such a series is made, it should be supplemented during the continuance of a flood by numerous special observations, which should determine the discharge of the river at its principal stages or variations of level. Floods, moreover, frequently occur at night time when it is not practicable to make observations. For these reasons for all important schemes it is advisable to have discharges registered by automatic flood recorders that will show all variations of level and the time during which they lasted (see Arts. 53 (*f*) and 55).

52. High-Flood Discharge.

(*a*) *Amount of Provision Necessary.*—The correct observation and calculation of the high-flood discharge are necessary in order to determine what provision should be made for dealing with it in an irrigation work. For cross-drainage works it is essential to allow sufficient waterway to pass the maximum rate of discharge, no matter for how short a time it lasts (see also Arts. 150 and 303). For reservoirs designed to make proper use of their flood-absorptive capacity (Art. 28 (*b*)) the waste weirs need not be constructed so as to be capable of dealing with this greatest intensity, as the flood rise of the storage will be comparatively a long and gentle one, but the works should be capable of disposing safely of the maximum total flood. For ordinary reservoirs which depend solely on their waste weirs, the latter must, like cross-drainage works, be able to pass off the maximum rate of discharge.

(*b*) *Conditions governing Flood Discharge.*—The conditions which govern the amount of high-flood discharge are similar to those producing yield (Art. 50 (*a*)), but the different factors have more pronounced effects. In addition, the general conformation of the area has a great influence on the maximum rate of discharge—a catchment roughly coinciding with a semicircle struck from the site of the work will tend to have large floods, seeing that the flow of the different tributaries will arrive thereat simultaneously, if their bed slopes, etc., are similar. Conversely, a long narrow catchment will probably have more prolonged and gentler floods, as the maximum flow of the most distant tributaries is likely to arrive at the point of discharge after that of the nearest streams has diminished. A storm travelling downstream will usually produce a larger flood than one crossing the catchment, and still larger than one going upstream.

Among the most important physical conditions tending to cause maximum floods are impervious, barren and steep slopes and high saturation of the surface of the catchment; also tributaries with steep fall flowing into a main stream with a gentle one. Of these the effect of saturation increases progressively with its amount, so that at the end of a prolonged and intense downpour most of the rain as it descends may run off. In tidal rivers the state of the tide, whether high or low, has a great influence on the height to which the rivers will rise in the lengths influenced thereby.

The principal physical conditions tending to reduce the intensity of floods are cultivated and flat slopes of the country, especially when dry and absorbent, and the presence therein of minor reservoirs, or swamps, of size sufficient to act as flood-regulators. Even the high-flood channel and margin of a very large river may have considerable flood-absorptive capacity, and thus may diminish the height and prolong the duration of a flood.

For attainment of safety the most favourable conditions for producing a maximum flood must be considered and provided against by the design of the work, as the consequences of disaster may be so serious to life, property and revenue (Art. 4 (*a*)).

(*c*) *Records of Floods.*—Where there are reliable records extending for at least twenty-five years, the highest flood observed, *plus* 10 per cent. extra for safety, may be taken as the discharge which the works should be designed to pass. If the record is a shorter one, the allowance for safety should be increased, unless in the period concerned an abnormally large flood had been observed. Such floods may occur at long intervals, but, nevertheless, provision for their safe discharge must be made in the works. When dealing with records, it is necessary to ascertain whether the existing general conditions remained unaltered during the period examined. Thus, if the country has recently been extensively afforested, the flood discharge is likely to be reduced. Should it have lately been largely disforested or drained, the flood discharge will probably be increased beyond what previously took place.

(*d*) *Observation of Floods.*—If there are no records available, local inquiry should be instituted, and as many flood marks as possible and on both banks should be ascertained and levelled, after necessary adjustments thereof have been made, and the probable discharge calculated therefrom. Although the height to which a maximum flood rose will be impressed on the minds of the local inhabitants, as they may not be trained observers who will have taken into account the effect of physical conditions in influencing flood levels, and as in course of time their recollection may have become defective, it is necessary that their statements should be carefully weighed. If after due inquiry the flood marks pointed out appear to be correct, they may be accepted, but an extra allowance should be made for safety.

(*e*) *Formulæ for Flood Discharge.*—For the calculation of high-flood discharge entire dependence is often placed upon formulæ, such as Dickens' and Ryves'.[1] In both these the high-flood discharge is given as the product of the drainage area in square miles, raised to certain powers, and a coefficient varying between wide limits, so that the selection of this is a matter of judgment, as it greatly affects the result. The catchment area is considered to be uniform from a hydrographic point of view throughout its extent, and of a general average character, and to be constant in its behaviour, that is, not affected by its degree of surface saturation; presumably it is assumed to be completely saturated, the condition which will produce the highest rate of run-off.

It is true that in many hydraulic formulæ there is a coefficient, but its limits of variation in most of them are not great, and all well-established formulæ are based on numerous experiments, or observations, where the conditions are simple, stable, and the same everywhere (e.g. those giving rates of discharge of channels of various sections; also, over weirs). Moreover, the wrong application of such formulæ does not usually involve danger, but only inaccuracy and loss. In the case of run-off formulæ, however, there are numerous indeterminate factors influencing the discharge, and most of these vary from area to area. Even the solid and apparently immutable catchment is extremely variable in this respect according to its degree of surface saturation (Art. 48 (*i*));

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[1] Dickens' formula is $D=CM^{\frac{3}{4}}$,
where D is the flood discharge in cubic feet per second;
M the catchment area in square miles; and
C a coefficient varying from 150 to 1,000 or more, and generally taken as 825.

Ryves' formula is $D=CM^{\frac{2}{3}}$,
where D and M are as before, but C varies from 450 to 675.

also, in a drainage area of any size there may be great hydrographic changes from point to point, so that it may be far from uniform (see Art. 103 (*b*), in which for the purposes of run-off calculation is given a method for reducing the actual varying catchment to an equivalent uniform area). The rate of travel of the floods in tributaries is not constant, as it alters with the depth of flow in them, and this variation affects the rate of discharge of the main stream. The intensity, duration, extent, and direction of the rainfall, being highly inconstant, cannot be represented accurately by mathematical symbols. All these factors are of much importance, and their extreme variability precludes their inclusion in a rigid formula generally applicable—in fact it is believed no formula makes the attempt to include them. Any great mistake due to a wrongly-used high-flood formula may involve, not merely inaccuracy, but danger to works, property and life.

Nature, however, takes all discharge factors accurately into account, and presents the finished solution of the problem—the actual resulting flood. All that is necessary is to observe, calculate, and tabulate the discharges of floods and utilise the information she thus gives. The more numerous are such observations, the more accurate will be the information obtained as to the flood-discharging capacity of the catchment. It cannot, however, be known with certainty if an observed high flood is the result of all its factors being themselves simultaneously at their maximum effect, so that to such flood must be added an allowance for safety when making provision for the proper disposal of the greatest flood possible. Observations of high floods should record notes of the degree to which the discharge factors came into action.

Notwithstanding what has been written above, a formula for high-flood discharge has the utility of enabling a preliminary general idea to be formed of the probable amount of a maximum flood. What is urged is that, whenever possible, this should be supplemented by actual observation of floods in the catchment under consideration, or, failing this, by taking into account the observed results of similar catchments in the neighbourhood.

(*f*) *Rate of Flood Discharge decreases with Increase of Catchment.*—One general law that has been established by experience is that the rate of high-flood discharge from small catchments is much greater than that from large ones having similar physical features. This depends upon the fact that intense rainfall is not precipitated simultaneously over large areas. On the other hand, heavy rain of less intensity may fall over very considerable tracts at the same time. Thus the typical curve of high-flood discharge for similar catchments with varying areas (represented by the abscissæ) has ordinates (representing the rate of discharge) greatly differing in length from each other for small areas and increasing more and more gradually as the areas extend, until, finally, the curve becomes asymptotic. In the case of very large rivers the maximum rate of discharge may possibly occur some distance above their outfalls; this is due to the fact that such rivers may have large flood-absorptive marginal areas, and the rate of flood-travel may decrease as the outfall is approached, owing to this and to the gradual diminution of the slopes of the country, and the decreasing intensity of the rainfall on the lower parts of the courses of the rivers.

53. Ordinary Methods of Gauging Discharge.

(*a*) *Necessity for Gauging.*—The gauging of a stream is necessary in order to determine the total amount, the maximum intensity and the duration of its flow. The total amount is the yield of the catchment, and this quantity, less that which has to be run to waste, is what can be stored or utilised. Upon the maximum intensity depends the extent of provision necessary for the safe discharge of high floods. The duration of flow combined with its amount indicates if a canal can be supplied solely by the stream or how much storage will be required to supplement the fair-weather discharge.

Streams are usually gauged by the following means:

Current meters;
Velocity rods, double and twin ball floats, or surface floats;
Observations of surface slope and cross-sectional area;
Weirs or notches.

(*b*) *Current Meters.*—A current meter enables the velocity at any point, horizontal or vertical, of the stream to be measured; it affords the only method of measuring the discharge of large and deep rivers. The instrument is first "calibrated" so as to compare its indications with those of the true velocities. The mean velocity of any vertical section has been found by observers to occur at from 24 to 25-fortieths of the total depth from the surface, and it will therefore ordinarily suffice to observe the meter at this depth only. A run of three minutes should be allowed to ascertain the velocity at the place observed.

An objection to the ordinary current meter is that owing to the space necessary for the revolution of the vane the velocity at the actual bottom of the stream cannot be observed.

(*c*) *Velocity Rods.*—A velocity rod is usually made of stout sheet tin and of about 1 inch in diameter; it has closed ends, and is loaded with shot, etc., so that it floats with its top projecting an inch or two above the surface of the water, and its bottom should clear the bed of the stream by about 3 inches. The rods are made in sets of lengths varying to suit the section of the stream to be gauged. The velocity of the rod, when that is immersed only about 0·94[1] of the depth of the stream, is very nearly equal to the mean one of the water, and hence to determine the latter it is then not necessary to apply a coefficient to the former. The instrument is the most accurate of ordinary floats, and is best adapted for use with depths up to 10 feet.

(*d*) *Double and Twin Ball Floats.*—The double float consists of a copper or other ball 2 or 3 inches in diameter attached by a very thin wire or thread to a disc of wood or cork, which floats on the surface. The twin ball float, is similar except that it has two balls, the lower of which is weighted, so as to preserve its true distance from the upper one, and this can be adjusted as desired. The floats record the velocities of the water at the points traversed by the balls as a little modified by the action of the current on the surface disc and connecting wire. If the centres of the balls below the surface are respectively 0·211H and 0·789H, where H is the depth of the stream, the float will register the true mean velocity of the water.[2] These floats are best adapted for use when the depth exceeds 10 feet.

(*e*) *Surface Floats.*—The surface float records only the surface velocity, and to this a coefficient has to be applied to obtain roughly the mean velocity of the section. This coefficient depends upon the hydraulic mean radius of the stream gauged. The float may be of any material which will not sink; corked bottles are often used, but the best form for ordinary gauging is a small wooden float conical at the top and hemispherical at the bottom, which, if necessary, is weighted; this form offers very little resistance to the action of the wind and is unbreakable.

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[1] Minutes of Proceedings, Inst.C.E., Vol. LXXI., p. 22. (Colonel A. Cunningham.)

[2] *Ibid.*, p. 19.

(*f*) *Gauging by Flood Sections.*—When there is not a proper gauging station, the discharge of a high flood can be arrived at by taking its cross-section and also its flood longitudinal section; the latter determines its general surface slope on which the mean velocity depends, and this can then be calculated. The longitudinal section can be made during the flood, or at any time afterwards, if the flood marks can then be ascertained correctly. The objection to this method is that during a flood the bed levels may be altered by the deposit or removal of detritus. The objection applies more to alluvial rivers with shifting beds than to non-alluvial streams with fixed ones. For important stations two flood-recording instruments should be fixed sufficiently far apart to show the slope, and these will indicate the water slope continuously on their diagrams (Arts. 51, end of, and 55).

(*g*) *Gauging by Weirs.*—Weirs form the most reliable ordinary means for obtaining very fairly accurate gaugings. For this purpose clear overfall weirs are the best, as their coefficients of discharge have been determined by numerous experiments. The discharge of a weir is affected by the position of its flanks with reference to the channel banks, which influences the way in which the stream approaches the work. "Complete contraction" takes place when the flank is distant from the bank at least three times the depth of the flow over the weir. Complete "suppressed contraction" occurs when the flank is flush with the bank. For complete contraction at the two flanks the usual allowance deducted from the length of the overfall is 0·2H, where H is the total flood depth; in long weirs with small flood depths this is a small deduction, which may be neglected.

If the area of the water passing over the weir exceeds one-fifth that of the approach channel to it, there will be velocity of approach (Art. 55). To obviate sensible velocity of approach the bed of the channel should be below the weir sill three times the depth passing over that, and each of the sides of the channel a similar distance from the ends of the weir sill. An objection raised to gauging by weirs is that the variation of the bed upstream by silting alters the velocity of approach. Another objection is that an ordinary weir of length suitable for gauging a small flow is not adapted to measuring a large discharge, and *vice versâ*. However, a weir can be made with a low notch section and upper general overflow crest to gauge flows of greatly varying amount.

(*h*) *Gauging by Notches.*—For gaugings of small flow clear overfall gauge notches are fixed; they are usually rectangular or triangular. To allow for the effect of contraction on rectangular notches the Cippoletti notch has been devised—in it the flanks are sloped back from the crest at ¼ to 1, and the discharge is thus due to its depth and the fixed crest length. The triangular notch has a right-angled, sharp-edged opening, with the apex at the sill, and the sides sloping equally therefrom, generally at 45° to the horizontal. The advantages of this form are that, in consequence of the similarity of the sections of discharge through the notches, the coefficient of discharge is practically constant for all depths gauged, and that therefore only the depth of flow need be registered as the width is taken into account in the formula giving the discharge:

$$D=\frac{4}{15}c\sqrt{2g}BH^{\frac{3}{2}}$$

where D is the discharge; c a coefficient$=0{\cdot}619$ when the angle of the notch is from 60° to 90°; B is the surface width, and H the depth of the flow.

Since $B=aH$ (where a is a constant depending upon the angle of the notch), the formula can be written:

$$D=\text{constant}\times H^{\frac{5}{2}}$$

A disadvantage is that a single notch can gauge only a small discharge; this can be met for flows of moderate size by increasing the number of notches.

54. Method of Gauging by Surface Floats.

(*a*) *The Gauging Run*—(i) *General Remarks.*—Correct gauging can be made only when the water flows with perfect regularity and with its surface undisturbed either by a rough bed and sides or by the wind. Gauging should be performed with intelligence, and should not be regarded as a mechanical operation. While the following notes relate to gauging by surface floats, many of them are applicable to gauging by other kinds of floats.

(ii) *Section.*—Both the longitudinal and cross-sections should be as uniform as possible in regard to bed and sides and direction of flow. For a series of gaugings at one place an artificial channel should always be made when practicable. This is best lined with planking, concrete, or plastered brickwork, etc., to preserve its form, and it is then known as a "flume." When the cross-section of a stream is greatly irregular, e.g. has wide, shallow sides and a deep central trough, each distinct portion should be gauged as a separate channel.

(iii) *Length.*—The length of the portion of the stream the velocity of which is to be gauged is called the "run." The run should be set out so that the float does not take less than 20, nor more than 50, seconds to pass down it. Any error in timing the entry or exit of the float will thus not greatly affect the result, nor will there be time to allow for external causes much to influence the flow of the float. The ends and centre of the run on each bank should be marked by pegs, etc., set out at right angles to its general direction.

(iv) *Breadth.*—If possible, this should be a multiple of 0·5, 1·0, 2·0, 5·0, or 10·0 feet to enable a hypothenuse table to be made and used for calculating the length of the wetted perimeter of the stream. That perimeter is equal to the sum of the slopes of the measured subdivisions of the section of the stream, and the square of each of these slopes is equal to the square of its horizontal projection and that of the difference of level between its ends.

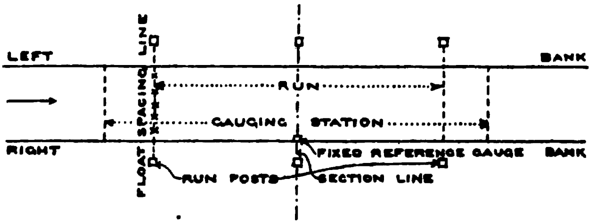
(v) *Flow.*—The motion of the float should be perfectly regular throughout and roughly parallel to the sides of the run. Floats moving with great irregularity should be neglected, and of course backwater and nearly still flows should not be measured. The velocity of an artificial channel should not be less than 1 foot, nor more than 3 feet, per second. In order that the float should enter and leave the run at the true velocity of the water, the gauging station should extend upstream and downstream for, say, 10 feet beyond the run (Fig. 18).

(*b*) *The Float.*—This should be light, so as to take the motion of the stream, but should present as little surface as possible to the action of the wind (Art. 53 (*e*)). The float should be dropped gently into the stream some few feet above the run and at the proper part of the section. For this purpose at the "float spacing line" a string or wire cable should be stretched across the stream and have tags fastened to it at intervals, between each of which the floats should pass midway. The float should not be followed immediately in the water by the gauger, as its motion will be affected by the eddies thus caused, and, for the same reason, it should, when necessary, be recovered well below the run. To increase the accuracy of the observations, the float may be made to travel from three to five times over each of its courses, and the mean velocities thus ascertained taken into account in the calculations.

(*c*) *The Gauges.*—The fixed gauge for obtaining reference depths for comparison and check of the series of gaugings may, for a small channel, be fixed in the middle of the central cross-section of the run, and be formed of an enamelled plate so as not to head up the water, but for a large stream or flume should be at the side, and for the latter may be painted on one side of the slope.

FIG. 18

GAUGING STATION



The movable gauge for taking the section of a channel of depth not exceeding 3 feet should be made of thin iron, with, if necessary, a flat base to prevent it from sinking into the bed. It should be held out from the body with its breadth parallel to the flow and the depth of water measured at the middle of its width by sliding a finger down it to the water surface. For greater depths up to 10 feet a sounding rod should be used, and for still greater depths a weighted sounding line. The instrument used should be graduated into feet and quarter feet for large depths, and into feet and tenths of a foot for small ones.

(*d*) *Distribution of Floats.*—The usual practice is to divide the surface of the water at the central cross-section of the run by marks on a string stretched across and above it, into intervals of equal lengths, and to drop the floats so that they may pass down the centres of the intervals. By doing this the small velocities of the intervals at the sides, where the depths are least, when summed arithmetically with the large velocities at the centre, where the depths are greatest, will result in an under-determination of the true average surface velocity. The correct method is first to obtain the cross-sectional area of the stream, then to divide this into the desired number of parts of equal area, and to mark the limits of these on a string stretched across the central section of the run, and, finally, to drop the floats so as to pass down the centres of these intervals. Each float will thus give the surface velocity of an equal area of the cross-section, and the mean of these velocities will be the true average surface velocity. A still more accurate method would be to divide the stream into sections throughout each of which the velocity is practically the same, and to measure the areas and velocities of each.

(*e*) *Timing.*—This is best effected by means of a watch with a second hand. If this is not available, a pendulum beating half seconds and enclosed in a box with a glass face should be used. The accuracy of the pendulum should occasionally be tested with a watch, and its length adjusted accordingly by screwing its bob up or down its rod.

(*f*) *Method of Observation*—*Rule* 1.—The following should be noted at the head of the record of observations:

The name of the stream or channel;
The situation of the gauging station on the stream;
The length of the run;
The reading on the fixed gauge;
The direction of the wind with reference to the flow, thus—upstream ↑, downstream ↓, across (90°) ⇄, oblique ↘↖ ↗↙;
The intensity of the wind, thus (see Art. 49 (*d*))—0=Calm, 1=Gentle Breeze, 2=Breeze, 3=Strong breeze; 4=Gale;

(*Note.*—As a rule, gaugings should not be made when conditions 3 and 4 obtain.)
The name of the observer;
The date and, if necessary, the hour of observation;
Remarks.

Rule 2.—The section should be taken by measuring the depths in feet and divisions of the regularly flowing water at equal intervals across the stream at the centre of the run.

Rule 3.—The section should then be divided into parts having approximately equal areas, by rough calculation from the section taken, and the floats dropped to pass centrally across them.

(*g*) *Method of Calculation—Rule* 4.—The sectional area in square feet, A, should be ascertained by summing the depths in feet gauged at equal intervals, less half the total of the end depths, and by multiplying the remainder by the common distance apart of the soundings.

Rule 5.—The wetted perimeter in feet, W.P., is the length of the line bounding the cross-sectional area of the water less the length of its surface. It can be determined by the use of a hypothenuse table (para. (*a*) iv); the difference in depth of each pair of soundings adjacent to each other should be ascertained, and the length of the part of the wetted perimeter, between them will be that given in the table corresponding to the distance apart of the soundings. The total length of the wetted perimeter will be the sum of these portions *plus* the depths of the ends, if these are vertical.

Rule 6.—The hydraulic mean radius, R, should be calculated thus—$R=\frac{A}{W.P.}$

Rule 7.—Determine, by reference to a table of coefficients, the coefficient C which reduces the observed average surface velocity of the stream, V_s, to the mean velocity, V, of the whole body of water.

Rule 8.—Determine the average surface velocity in feet per second, V_s, by dividing the total distance in feet travelled by the floats by the total number of seconds taken by them. This can be found from a prepared table if the total distance travelled is a measure of 100 feet. If it is not, it should be multiplied by a number to become such a measure, and the corresponding velocity in the table divided by the same number.

Rule 9.—The discharge, D, of the stream in cusecs is equal to AV. To obtain it, first calculate A; next W.P., from which find R, and from this C; then calculate V_s and multiply it by C to arrive at V, all as above noted, and then multiply A by V.

55. Gauging by Weirs.

The discharge of a clear overfall weir varies with its cross-section, and therefore, when the formula to determine the flow is selected, it must be seen that the weir is of the same section as that of the experimental one used in arriving at the formula. In particular, it is necessary that there should be free admission of air between the sheet of water falling over the crest and the face of the weir, as this was arranged for in the experimental observations on which weir discharge formulæ are based so as to obtain a fixed condition. The gauge for determining the depths of flow should be sufficiently upstream of the weir or away from the overfall to be in still water, so as to indicate the true afflux height, and may conveniently be placed near the bank on a long flank. Where still water cannot be obtained, the velocity of approach should be measured and the head corresponding to it added to the observed depth on the gauge (Art. 53 (*g*)).

The head—h_a—due to the velocity of approach—u—is—

$$h_a=\frac{u^2}{2g}$$

and the total discharge Q in cusecs is—

$$Q=\tfrac{2}{3}cb\sqrt{2g}\left\{(h+h_a)^{\frac{3}{2}}-h_a^{\frac{3}{2}}\right\}$$

where c is a coefficient varying for different values of $\frac{b}{h}$ and has to be determined experimentally,

b, the breadth of the weir in feet,
g, the acceleration of gravity in feet per second, and
h, the observed depth of flow in feet over the weir.

Taking the mean value of $c=0{\cdot}622$ and $\sqrt{2g}=8{\cdot}025$, the formula becomes—

$$Q=3{\cdot}33b\left\{(h+h_a)^{\frac{3}{2}}-h_a^{\frac{3}{2}}\right\}$$

If end contractions have to be taken into account, b has to be reduced by $0{\cdot}2h$.

In all cases the zero of the gauge should be exactly at the level of the gauging crest. For accurate measurements the depth should be read by means of a hook gauge. For the correct observation of the total flow over a weir a weir recorder should be fixed so as to record the depths of discharge continuously on its diagram, which is revolved by clockwork, and has its line marked by a pen that follows the fluctuation in height of the discharge.

Although drowned weirs are not used for gauging, their discharges may have to be determined when they form part or the whole of waste weirs. The formula for their discharge is:

$$Q = cb\sqrt{2gh_2}\left(h - \frac{h_2}{3}\right)$$

where h_2 is the difference in feet between the afflux and tail levels, and the other symbols have the same values as in the preceding formula.

A waste weir may consist of all or any of the following sections:

A clear overfall for both small and high floods;
A clear overfall for small floods changing into a drowned weir as the flood increases;
A drowned weir for all floods;
A channel for all floods.

To ascertain the discharge under varying flood conditions of a weir comprising many different sections, the tail channel should be gauged and a table made of the discharges corresponding to different gauged depths on the weir.

For each gauge station it will be advisable to make out a similar table of discharges corresponding to observed depths. The results of the observations can then be tabulated easily, so as to ascertain the total flow during any period considered.

CHAPTER. IV.

PROJECTS AND WORKS.

56. Aphorisms and General Principles.

(*a*) *Aphorisms.*—(i) A well-regulated imagination is a valuable possession to an engineer; he should be able to foresee possibilities, but should have regard to probabilities.

(ii) The experience of the past, modified by later knowledge, should be the guide for the present.

(iii) The impossibilities of the present are often the practicabilities of the future.

(iv) Nature should be taken as an example[1] but should, when necessary, be improved upon; she is generally lavish in her operations, and methods more economical than hers can often be adopted.

(v) Irrigation entails co-operation—in small works by the people, in large ones by the administration and the people.

(*b*) *Supply.*—(vi) The third place of decimals in hydraulic calculations indicates a degree of accuracy which cannot be attained in the existing state of knowledge, and one which, if it could be ensured, would be only of theoretical value. What are required are practical accuracy and avoidance of error.

(vii) A correct knowledge of the quantity of water to be dealt with is essential for the proper design of works for storage, flood disposal and distribution. To obtain that knowledge investigations should, within reason, be as numerous and as prolonged as possible.

(viii) For easy regulation of supply, it is better that each scheme should be self-contained, and not dependent on another.

(ix) Water should be kept at the highest level practicable in order to obtain the maximum command with the minimum length of channel. For this reason stored water should not, as a rule, be dropped to pass down a river to be subsequently caught by an intake weir for diversion into the canal system. Fed reservoirs supplied by canals involve the lowering of water from their own full-supply level to that of the channels led from their outlets.

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[1] Compare: Pools below waterfalls and water cushions, birds and heavier-than-air flying machines; diversified colour of animals and artillery to secure invisibility.

(x) The flow of streams lasting throughout the fair season, or even for some months only, should be utilised as much as possible to save the cost of, and loss by evaporation from, storage in reservoirs.

(xi) Rivers with a large perennial flow furnish the most certain and cheapest supply for irrigation. Water is thus obtained at the highest level, in closest proximity to the fertile bottom lands, and with the minimum loss from evaporation and in transit.

(xii) Water derived direct from rivers is generally of a more fertilising character than that which has been clarified by having been stored in reservoirs.

(xiii) Reservoirs are desirable to make good the fluctuations of rivers with a long-continued flow; they are essential for perennial irrigation if the stream flow is short-lived, unless supply when deficient can be made good by wells.

(xiv) Water should be under control from the time it enters until it leaves an irrigation system. It is a good servant, but a bad master.

(xv) Drainage should be provided whenever lands are liable to be flooded, to become water-logged by the rise of subsoil water, or to be injured by the efflorescence from subsoil salts. Frequently the necessity for drainage is an indication of over-irrigation, and may then be reduced or obviated by restricting the supply of water to the fields.

(*c*) *Projects.*—(xvi) When schemes are being designed, local experience should be consulted and combined with scientific knowledge, so as to get the best results.

(xvii) A project should not be undertaken until the whole of the neighbourhood has been thoroughly examined to see that no better scheme exists in it.

(xviii) The head of a catchment should, from an engineering point of view, be dealt with first, and lower projects constructed in the order of their nearness to it. Where this is not practicable, it should be seen that the lower projects will not interfere with the construction, or scope, of upper ones to be taken in hand subsequently.

(xix) Irrigation systems should be compact, and, as a rule, confined to one main catchment. The irrigated area should be concentrated, and isolated tracts avoided.

(xx) The land near the headworks can be irrigated with the least loss of water in transit; thus it is desirable to gain command as quickly as possible, and to have the irrigable area as close as practicable to its source of supply.

(xxi) Schemes should, when necessary, be made expansible to allow for the requirements of increased irrigation. An initial large capital expenditure, providing for irrigation on a scale largely in excess of what is likely to take place early, will result at first in comparatively small gross revenue, and the net revenue will be out of proportion smaller, owing to maintenance charges being increased by the size of the scheme.

(xxii) Projects should be designed to meet the probable requirements of the near future. Enthusiastic ideas of possibilities may never be realised.

(xxiii) The most favourable conditions for the success of a scheme are—water must be required; enterprising and skilled cultivators must be numerous or colonists procurable; the works must be completed early and made ready in all respects for irrigation; the irrigated area must be compact, fertile, and near good markets, to which communication should be good; the capital cost of the works must not be excessive nor the irrigation rates high, and the net revenue must be fair in amount.

(xxiv) Large projects are relatively the cheapest to construct and maintain. If successful, they will justify the employment of superior establishment to control them; they will enable cultivation to be conducted most cheaply, as they will permit of the economical use of labour-saving appliances; they will be of substantial benefit to the country as a whole; and they will tend to its development by an extension of railway or other communications.

(xxv) If large works are unsuccessful, they will constitute a financial burden on the country, and be a set-back to further progress in irrigation.

(xxvi) Medium-sized projects have advantages and disadvantages midway between those of large and small schemes.

(xxvii) Small projects are alone possible on isolated small catchments, and are the only ones which will develop such areas, which without them would not make use of the water supply available. They are comparatively expensive in cost, maintenance, and supervision, and generally have not the indirect advantages of large schemes; but if failures, do not involve much loss or discredit.

(xxviii) Existing works should be utilised as much as possible, except when their design, alignment, or construction is so defective as to render their improvement undesirable.

(xxix) Although full and careful consideration of a project is necessary, many revisions of a scheme entail waste of money and time. It is quite possible that the original designer was more correct than his successors in selecting the alternative treatment most suitable to the conditions to be met, but erred in not fully recording his reasons therefor. In comparing the alternative treatments recommended due weight should be given to the professional ability of the different designers of the project.

(xxx) The character of the communications required to develop an irrigation area depends upon the size of the irrigation scheme. A large canal system justifies the construction of a railway; a medium-sized project may be properly served by a good road or tram line; while a small scheme may not want more development than improvements to existing roads.

(xxxi) When a line of communication competes for location with an irrigation scheme (e.g. a road crossing a reservoir basin), the former should give way to the latter, not since it is of less importance, but because otherwise it might render irrigation impossible. A road or railway may be diverted a little, generally at small expense; the line suitable for a dam may be the only one financially and physically possible for it. Sites for reservoirs should therefore be reserved as early as possible for their construction when desirable.

(xxxii) Water-supply projects should not be combined with irrigation ones, unless the draw-off required for the former bears a small proportion to the total amount of water available. The demands of water supply having first to be met, only the balance can be devoted to irrigation, and the amount and irrigating capacity of that will greatly be reduced in seasons of bad replenishment if this rule is not observed.

(xxxiii) When power schemes are combined with irrigation ones, provision for an auxiliary stand-by system should be made to meet the fluctuations in draw-off of water for irrigation in accordance with the varying demands of cultivation. The stand-by may consist of a steam or other power station, or of a subsidiary reservoir affording supply to supplement that from the main reservoir when the latter is reduced for any reason.

(*d*) *Design.*—(xxxiv) All works should be designed to be safe under the severest conditions to which they may be subjected. Thus, the height of the top of a dam should be calculated with reference to the high-flood level, and not the full-supply level of the reservoir. A waste weir, a reservoir outlet, and a cross-drainage work should be planned so that the discharge of each will not be interfered with by trees, brushwood, etc., carried down by floods.

(xxxv) Entirely novel designs should, as a rule, not be made; it is granted but to few to strike out quite new departures successfully. Well-tried designs should preferably be adopted as general guides, and be improved upon as practical experience, the actual test, dictates. Evolution, not revolution, should be the aim of the engineer.

(xxxvi) Designs should be of as simple a nature as possible, and should meet actual conditions. Irrigation works have to deal not with pure distilled water, but with water which may carry with it silt, gravel, boulders, brushwood, and trees.

(xxxvii) All works should be designed (with provision of steps or other means of access) so that they can easily be inspected by an ordinary man, and not only by an acrobat.

(*e*) *Works.*—(xxxviii) Works should be of a solid, permanent character to reduce maintenance charges, but should be duly economical in design and construction so as to lessen capital and maintenance costs. The character of the works should be simple, for, these being situated as a rule in out-of-the-way places, expensive display is unnecessary, e.g. ashlar is seldom needed, and when required should be sparingly used, and only for important parts.

(xxxix) Soundness of construction is essential for an irrigation work, especially when it has to withstand the unceasing action of water, day and night, year after year. Most other engineering constructions on land are subjected to test only at long intervals and for short periods, and, if endangered, can be put out of action until repairs are effected. Also the failure of an irrigation work is more likely than that of an ordinary work to entail great destruction of life and property; its repair may moreover, be difficult and expensive to effect.

(xl) In irrigation works the greatest care is required in dealing with the foundations so as to secure water-tightness and permanent soundness. The repair of defective foundations is in some cases practically impossible, and in others generally difficult.

(xli) The design of the works should have reference to their size and importance. A tortuous alignment may be admissible for a field distributary, but it is not desirable for a large canal.

(xlii) As a rule, on account of the size of the works and of the usually small financial return from them, local materials have to be used for the construction of irrigation schemes. The engineer can best show his capacity by making the most of local conditions.

(xliii) Subsidiary works should not be commenced until the main ones are approaching completion, that is, they need not be finished long in advance. Any alterations in design of the former, indicated by experience gained on the latter, may thus be effected without change of construction. Moreover, the capital sum will thus be relieved of some interest charges until just before the scheme begins to earn revenue.

(xliv) Works should be constructed, or restored, before land or other compensation [1] becomes expensive.

(xlv) Failures, properly considered, teach more than successes. He who never makes a mistake, never makes anything worth the making.

(xlvi) The extensive failure of an irrigation work entails not only the cost of its repair, but may lead to the loss of crops, the value of which in one season may approximate to that of the entire work. Such failure will lower the prestige of the administration, will lessen the confidence of the irrigators, which may not easily be restored, and may thus retard the growth of irrigation.

(xlvii) Repaired works are seldom as safe or satisfactory as those which do not require repairs.

(xlviii) During construction it is not advisable to change the members of the staff, especially the superior ones; thus they will continue to gain experience, which will conduce to economy and rapidity of execution, while responsibility for the proper carrying out of the works can then more easily be fixed.

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[1] The cheap acquisition of land required for public purposes was dealt with by the British Parliament in 1919.

(*f*) *Financial.*—(xlix) It is false economy to pare down works during construction, in order to avoid an excess, etc., as alterations subsequently found necessary are difficult to construct when the irrigation scheme is in operation.

(l) It is advisable to reduce maintenance expenses as much as possible, if necessary by an increase in capital expenditure, even if that may amount to somewhat more than the capitalised value of the saving. This will diminish the subsequent cost of establishment, and will increase the efficiency and security of the work.

57. Investigations and Reports.

(*a*) *Reconnaissance Survey.*—Before a project is selected for detailed investigation, it is essential that the whole of the country in its neighbourhood should be examined by means of a reconnaissance. The principal objects of this preliminary survey are to obtain, at comparatively small expenditure of time and money, general information as to the nature of the tract examined, the facilities offered by it for irrigation, and the relative merits of all projects practicable in it. Such a reconnaissance enables a general plan to be drawn up so as to utilise those facilities in the best and most comprehensive manner possible, and so that each individual project proposed will work in, and will not clash, with other schemes feasible. Thus will be avoided the fatal mistake of carrying out irrigation work in a piecemeal way without reference to an all-inclusive plan.

To enable a proper comparison to be made of the relative advantages of competing schemes, approximate general surveys of the works and irrigable areas should be undertaken, and rough plans and estimates of the proposed works should be made. The designs for these should not be considered as final ones, nor the estimates for them as exact, but sufficient care should be taken in their preparation to obviate extensive alterations thereafter, as those may greatly lessen the value of the preliminary work. In particular, that work should be based on cautious assumptions of the nature of the foundations, the character of the designs, and the costs of the construction, as it is almost the invariable experience that the estimates of detailed projects amount to more than those of preliminary ones. Care should also be taken to prepare the designs and estimates of competing projects as far as possible on the same general lines, so that a fair comparison as to their costs and advantages may be obtained.

After the reconnaissance report has been prepared, it should be considered by all concerned, e.g., an administration would consult its various departments as noted below.

(*b*) *Other Preliminary Investigations*—(i) *Hydrographic Survey*.—As soon as it has been ascertained that a favourable scheme is practicable in the area under reconnaissance, all hydrographic investigations necessary (Arts. 4 (*c*) and 56 (vii)) should be started, and they should be continued for as long as possible.

(ii) *Revenue Department*.—This should report what is the existing population affected by the scheme, whether that is sufficient to justify its construction, and, if not, what probability there is of an increase of the cultivators by immigration, etc.; what is the character of the people, whether they desire the work and will take advantage of it; what is their financial status, and if they are willing and able to pay the water rates proposed; if the works are necessary to improve the cultivators' condition; what are the prospects of trade development; what markets are available; whether capitalists will be attracted; what is the state of the labour supply for the execution of the works; and, generally, if from the revenue and administrative points of view the scheme is desirable or not.

(iii) *Agricultural Department*.—This should note if the soil is suitable and the water good for irrigation; if drainage will be necessary; if cattle and manure are sufficient; what crops can best be grown; and, generally, if the agriculturable conditions are favourable.

(iv) *Survey Department*.—This should state if the land plans and record are complete for the area concerned, and if not, what is required to bring them up to date, and how long this will take to effect.

(v) *Forest Department*.—This should intimate how the proposed scheme will affect its operations, what is the quantity of timber standing on the irrigable area and that required for the works, and if it can be disposed of at good prices.

(vi) *Public Works Department*.—This should give a rough idea of the cost of constructing any new communications, or improving or altering existing ones, which the project may require for its development.

(vii) *Geological Department*.—This should advise on the general geological conditions, and indicate what special precautions are necessary to ensure the safety and success of the works.

With all this preliminary information before it, the administration will be able to decide if it is, or is not, desirable to prosecute the detailed engineering investigation necessary to arrive at a more correct idea of the probable cost of the scheme. The preliminary reports mentioned above are, of course, required only in the case of a project of some magnitude involving a considerable amount of expenditure. For a small proposal it will suffice if the Revenue Department alone gives its general opinion of the desirability and necessity of the work from its standpoint.

58. Final Reports.

(*a*) *Engineering Report.*—When it has been decided that the prospects of a project are sufficiently good to justify its detailed examination, final surveys should be carried out, the complete designs prepared, and the precise estimates made. The final report embodying all this work should explain everything in connection with it in non-technical language, so that all who have to deal with the scheme may readily understand the proposals. While the report should be concise, it should be full, so as to record in one place the history of the scheme, the reasons which influenced its selection, its scope, and the results anticipated from it. The report should be accompanied by the following documents:

Statistical information relating to the project;
Recapitulation of the different estimates;
Index plan (showing the location of the project with reference to towns, villages, markets, roads, railways, and other irrigation works, and the proposed canal system and the area irrigable by it);
Hydrographic tables of river and waste weir flood discharges, rainfall, storage, etc.;
Forecast of the probable revenue and the financial return for the first twenty years;
Departmental opinions of the project in its preliminary stage.

(*b*) *Other Reports.*—It is quite possible that the final irrigation report may show that the scope and financial prospects of the scheme, as outlined in the preliminary report, have been materially altered. It is therefore necessary that this final report should be referred to the departments which dealt with the preliminary one, so that, with further information before them, they may have the opportunity of making their own final reports. The administration will then be in possession of a completely drawn-up scheme, and of the matured opinions of all those who have examined it from their departmental points of view, and will be able to come to a decision as to whether the work should be constructed or not. The procedure described is lengthy, but is advisable, as an irrigation scheme should never be rushed through, or else there is a chance that disaster—constructional, hydrographic, or financial—may attend it, which would not only cause loss to those concerned, but would act as a set-back to irrigation development generally.

(*c*) *Extent of Investigation Necessary.*—The principal cause of failure of certain irrigation projects was undue haste in their preparation, whereby time was not allowed to obtain correct data on which to base the designs. An excessive amount of investigation and the preparation of numerous alternative or revised schemes are also to be deprecated, as frequently matters which have already been fully enquired into are lost sight of, and thereafter reopened *de novo*, and sometimes the reasons which led originally to correct decisions are forgotten and mistakes are thereby made. Such prolonged preparation is not only costly, but also disheartening to those who have to continue it, as they will be doubtful if their recommendations will be accepted and embodied in an executed work.

59. Irrigation Surveys.

(*a*) *General Remarks.*—An incorrect survey may lead to the condemnation of a good scheme or to the recommendation of a bad one. An insufficient survey may stop progress in designing, and necessitate supplementary field work; in all cases, therefore, the survey should extend not only over the area selected for the works, but sufficiently beyond their proposed sites, so that desirable alterations of location can be made in office. In flat country particular care is necessary to see that the levels downstream of the proposed work will not interfere with it. All survey should be carefully recorded in the books, so that it may be picked up at any time, and for the same purpose permanent marks should be left on the ground at close intervals and benchmarks near the sites of all important works, cuttings, and embankments. Checking of survey work should take place frequently so that the correctness of each section may be established early and cumulative errors avoided. It is advisable that the check levels should be run over the same stations as those of the original work, preferably in the reverse direction, so that any errors there may be may at once be located and the levels re-checked. The starting reduced level for canals should be the sill of the head regulator, and for independent reservoirs and weirs, the full-supply level—easily remembered round numbers should be given to them. The starting point for distances should be the upstream face of the head regulator wall for main canals and that of the cross regulator for branch canals.

(*b*) *Storage Reservoirs*—(i) *The Catchment Area.*—The probable amount of water that can be stored in an average year depends upon the then run-off from the catchment, and therefore the extent of that area must be determined. Where good topographical maps exist, the bounding watershed line can generally be determined by inspection with them on the ground; otherwise, that line must be ascertained by a traverse survey.

(ii) *Reservoir Storage Capacity.*—For large schemes this is determined by running contours, usually 10 feet apart vertically, over the area of the reservoir basin. To enable the storage capacity table to be made out, intermediate contours 1 foot apart can be interpolated by calculation. For small projects parallel cross-section lines can be run across the basin, and the contours can be deduced from them. The survey should extend beyond the high-flood limits originally contemplated, so as to permit of an increase of them if subsequently found desirable.

(iii) *Survey for Works.*—A trial longitudinal section of the dam should first be surveyed and the area in the immediate neighbourhood contoured at 2 or 4 feet vertical intervals, so that any necessary alteration of the alignment can be made in office by means of rough estimates of different suitable lines. The longitudinal section of the line thus finally selected should be levelled and plotted. Similarly, longitudinal sections of the waste weir, its tail channel, and the outlet channel should be taken.

For earthen dams the areas from which the different soils required for construction are to be obtained should then be surveyed and plotted, and small trial pits excavated to test the depths of the soils. From this plan a tabulated statement of quantities, leads, and lifts should be prepared so as to ascertain the general earthwork rate to be allowed for construction.

(*c*) *Weirs and Headworks*—(i) *River Survey.*—The length of the river likely to be affected by the construction of the works should be surveyed, and on its plan should be shown all the alternative sites selected for investigation, and the area of the flood-afflux backwater. Longitudinal sections of any flood embankments necessary should be taken.

(ii) *Weir Sections.*—A longitudinal section and a few cross-sections for the main weir should be taken, and one of the latter should be run for some distance downstream along the deep channel of each branch of the river to determine its general fall. If a subsidiary or water-cushion weir is to be constructed, similar sections are required for it.

(*d*) *Canals*—(i) *Canal Alignment.*—The longitudinal section and plan of what is at first considered the best alignment should be surveyed and cross-sections taken at intervals, especially at important points, such as main ridges and valleys crossed, so that deviations as required can be drawn in office. In hilly and rolling country a better plan is to run three contours, falling at the inclination proposed for the bed slope of the canal and from 5 to 10 feet apart vertically; the central one should be on the line originally selected for the canal. Different survey parties can be employed on these lines, and thus a continuous check on the work can be obtained during the survey. As the field work proceeds, the final alignment should be decided section by section, so that the survey of the downstream lengths may be kept as close as practicable to their finally determined location.

In flat country a contoured plan will be of great assistance; if not available, one might be prepared by running cross-sections from a trial falling contour, or by running three falling contours from one-eighth to one-half a mile apart as described above.

(ii) *Cross-Drainage Works.*—Where cross-drainage lines are met they should be surveyed for some distance both upstream and downstream of the canal line, so that the best crossings may be selected, and the high-flood longitudinal and cross-sections of the streams should be levelled with a view to determining their maximum discharge. The proper location of cross-drainage works is of much importance, as on it depends to a great extent the safety and economy of the whole system; much care should therefore be taken to ensure that it is correctly selected (Art. 113, end of (*a*)). All surveys for these works should be connected with that of the main canal.

(iii) *Trial Pits.*—As soon as the canal alignment has been settled, trial pits should be dug along it at intervals depending upon the variation of the subsoil, and especially where there will be deep cuttings or hard excavation, and also at the sites of all large masonry works. For the last-named the pits should extend beyond the depth proposed for the foundations, so that the nature of the substrata may be known. Deep trial pits are required to determine the nature of the foundations of a storage dam and its outlet, and usually less deep ones along the lines of waste weirs and weirs.

(iv) *Surface Information.*—The nature of the surface of the ground should be recorded on the plans, and also if the soil is impregnated with salt, and, in the case of canals, if the area passed over is liable to be flooded.

(*e*) *The Irrigable Area.*—When the country is flat[1] the area commanded by the main canal should have cross-section lines run across it at every quarter of a mile or 1,000 feet, and also a similar set of longitudinal section lines; the intersection points of every alternate pair should be marked by permanent bench marks levelled to one-tenth of a foot. This survey should extend somewhat beyond the irrigable area, if that is not bounded by a main drainage line limiting it, so that the general lie of the country downstream may be ascertained. From the levels of the section lines the contours of the area can be laid down on the general plan; on this the main drainage lines and water-courses should be shown, and their bed levels entered at intervals, and the unirrigable areas should be marked. The distributaries, minors and watercourses (Art. 2 (x)—(xii)) can be laid down on this plan, and the areas of their command, their bed slopes and sizes, determined from it; thereafter they should be surveyed and levelled. Where there are several survey parties at work it is advisable that the boundaries of the areas dealt with by them should be fixed on ridge lines.

When the country has steep slopes and well-defined water-courses, a contoured plan is not so necessary, although one is desirable. In such country, when it has been marked out in fields and a cadastral survey showing the fields has been made, it may be possible to mark by eye on the plan with reference to the field boundaries the reticulation of the natural minor drainage lines ; if this is done, the alignment of the distributary system along watersheds can easily be determined.

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[1] A full account of irrigation surveys is given in "Irrigation Works in India," by Lieut.-Colonel J. Clibborn, C.I.E. Thomason Civil Engineering College, Roorkee, India.

60. Plans.

The following list of plans comprises all those generally required :

(*a*) *Index Plan*—(Art. 58 (*a*)).—Usual scale 1 mile to 1 inch. This should be a tracing of foolscap size, or folded to it, so that it may be bound with the report ; a duplicate of it should be placed with the other plans.

(*b*) *Storage Reservoir*—(i) *General Plan of the Catchment.*—Usual scale 1 mile to 1 inch. If topographical sheets exist, this plan should be prepared from them ; the bounding watershed line should be clearly marked, and the area in square miles of the catchment printed on the plan.

(ii) *Contoured Plan of the Reservoirs.*—Usual scale 660 feet to 1 inch. The plan should show all the main contours and also all the works connected with the reservoir, particularly the tail channel of the waste weir and its outfall ; a table of the areas and capacities of the main contours should be printed on it.

(iii) *Land Plan.*—Usual scale 660 feet to 1 inch. The plan should be prepared from the Government land plans, if there are any, and should show all land to be acquired, and the offsets from existing fields to where its boundary changes in direction.

(iv) *Dam.*—Plan, longitudinal and cross-sections ; details of foundations and closure arrangements.

(v) *Waste Weir.*—Plan, longitudinal and cross-sections ; details of sluices and temporary gates.

(vi) *Outlet.*—Plan, longitudinal and cross-sections ; details of tail- and fore-bays, approach bridge, valves, lifting rods and capstans.

(*c*) *Weir or Headworks*—(i) *Contoured Plan of the Backwater.*—As for reservoirs.

(ii) *Land Plan.*—As for reservoirs.

(iii) *Flood Embankments.*—Longitudinal and cross-sections.

(iv) *Headworks.*—General plan showing all works; longitudinal and cross-sections; details of all sluices.

(*d*) *Main Canal and Branches*—(i) *Longitudinal Sections.*—To show canal bed and full-supply line, ground line, and top of embankment; the location of all proposed works to be indicated. Notes to be given of the bed fall, full-supply discharge and the irrigable area under command of different sections of the canal.

(ii) *Cross-sections.*—To be given of all type and unusual sections.

(iii) *Cross-drainage and Other Works.*—Plan, elevation, and cross-sections of each main work to be drawn. For minor works type designs to be prepared.

(iv) *Plan of Irrigable Area.*—On this to be shown all villages, roads, etc.; the main canal and its branches and sites of the principal works; drainage lines and channels and the boundaries of irrigable and unirrigable land.

(*e*) *General Remarks.*—The plans should be complete so that the scope of the project may easily be ascertained from them. The scales for the drawings should generally be chosen so that these may be as small as is consistent with the clear indication of the detail necessary. Large, unwieldy drawings are inconvenient to deal with, and are usually unnecessary, as intricate parts can easily be shown separately in enlarged detailed drawings. The original sanctioned plans should be bound unfolded, and should never leave the office of record. Each engineer who requires drawings should be supplied with copies for his guidance, preferably in duplicate, so that one set may never be taken on the works themselves, as there they are likely to get injured. It will be convenient if tracings are folded foolscap size and docketted outside with their names, and for easy reference are bound together in book form, or placed in portfolios, each book or portfolio having outside an index list of the drawings it contains. After a work has been constructed a set of completion drawings should be prepared; these should record exactly how it has been executed, major deviations from the original sanction should be clearly shown, and all foundation lines and levels should be entered.

On every drawing, as required, the foundations and the trial pits by which they were determined should be marked; the direction of the flow of water should be indicated by arrows; and all reduced levels, water lines, and levels should be carefully given, so that the plans may be complete in themselves. Each plan should bear—the name of the project and its own distinctive name; the year of its preparation; the estimated cost of the work; its own project number and its general register number; the names of the surveyor, designer, and draughtsman, and references to bench marks and to the pages of the field book in which the survey is recorded.

61. Estimates.

(*a*) *General Remarks.*—An estimate is a very important document; it cannot be prepared too correctly nor recorded too carefully; it should be susceptible of being checked at any time; and it should be in such detail that it will afford guidance during construction. Estimates for schemes should provide for everything required; they should not be made piecemeal, as thus a proper idea of the cost of the works cannot be obtained, nor can it be seen whether the project should be undertaken or not; supplementary estimates should therefore be avoided. The preparation for the whole project of very small estimates for minor parts of a scheme, however, gives unnecessary trouble, and it will therefore suffice to make in the main estimate only lump sum provisions for them.

An estimate is a forecast of expenditure to be spent, and is not a bill of costs actually incurred. It should therefore be framed so that its amount may provide for executing a work in ordinary circumstances as far as can reasonably be foreseen, and should not allow for unforeseen requirements except under "contingencies," the provision for which should entirely be devoted to meet these. "Tight" estimates will induce every one concerned to be as economical as possible; "loose" or inflated ones may have the opposite effect. The former are therefore to be preferred to the latter on the understanding that, if subsequently excesses are justifiably incurred, they will be admitted if reported as soon as they are seen to be unavoidable.

(*b*) *Project Estimates.*—Estimates for reconnaissance or preliminary reports do not require to be made out in great detail, because sanctions to them will not be given, nor will works be constructed in accordance with them; they are required solely to give a fair idea of the cost of a scheme. To mark their approximate character they should be in round numbers, and lump sum provisions should be entered in them for subsidiary works; care should, however, be taken to include all such works, as the omission of some of them might considerably affect the total sum. It will greatly assist the accurate preparation of such estimates if statistics are kept of the actual cost of construction of completed works, such as the rate per mile of distributaries, the rate per cusec of discharge of canals of different sizes, the cost of type designs of outlets, sluices, bridges, aqueducts, etc.

(*c*) *Detailed Estimates.*—The estimates of the different works included in a project should be indexed in a " recapitulation " showing the total cost of each work arranged under main heads of account. The individual estimates should then follow in the order of this recapitulation; each should consist of a " general description," the detailed " measurements," and an " abstract " of the cost. The general description should be confined to an explanation of the drawings and to any tabular information required in connection with the work; the reasons for selecting any particular type of work, or for adopting any novel features in its design should appear in the report forwarding the project. The measurements under the different subheads should be arranged throughout in the same order, so that the total quantities and costs of any particular part of the work may be readily ascertained at any time. A sheet explanatory of how the principal rates have been arrived at should be attached. The abstract should be made out as a tabular statement, giving in columns the quantity, the description of the item, the rate, the unit at which the rate has been calculated, and the amount, or cost, in whole numbers; for easy reference in account documents in which allocations of expenditure are made, each item should be given a distinctive number. The abstract should show the total cost of each subwork, including its " contingencies," and the grand total cost of the work.

Attached to the estimates should be a " specification," prescribing how the different descriptions of work are to be constructed. It should clearly distinguish between what is ordered and what is left to the discretion of the principal responsible officer on the work, and as much latitude as possible should be given to him to meet unforeseen requirements.

The object and scope of each of these project documents may thus be stated. The report should explain the scheme so that it may be understood by the unprofessional, as well as by the professional, officers who will have to deal with it, and should particularly describe any unusual features in it. The recapitulation of the estimates will furnish financial authorities with the data they require. The general description, taken together with the plans, will make clear the engineering features of the scheme ; the measurement sheet will be a guide in construction ; the abstract will enable a check to be maintained on the cost of the work ; and the specification will describe the way in which the different items are to be executed. These observations should be borne in mind so that each document may be complete in itself, and may not duplicate subject matter which should find its place only in the document properly elative to it.

CHAPTER V.

LARGE RESERVOIRS.

62. Location.

(*a*) *General Remarks.*—When choosing a site for a dam it should be remembered that generally the longitudinal section indicates the cost of the scheme; the sites available for waste weirs and outlets its feasibility; and the nature of the reservoir basin, whether open or confined, the relative cost of storage. Moreover, the dam must be located where the catchment above it is sufficient to produce the required storage in average years, but is not excessive, and where the foundations are sound, the reservoir basin water-tight, and materials for construction are ample and cheap.

(*b*) *The Dam.*—The best site for a dam is usually one which has ridges running down from high land on both sides to the stream to be impounded. Such ridges, if high, will greatly reduce the cost, as the section of a masonry dam increases considerably with its height, and that of an ordinary earthen dam varies roughly as two-and-a-half times the square of its height. Long, low dams may thus be cheaper than short, high ones to construct originally and to raise subsequently, and also safer.

For an earthen dam it is best that both sides of the river gorge should be fairly similar, with not too steep slopes, so that the dam may be symmetrical across the stream and its cost a minimum one. If, however, only one side is steep and the other much gentler in slope, the safety of the dam is practically not prejudiced, as the flank embankment on the latter will form a sufficient abutment to the gorge portion of the dam. Moreover, this gentler slope may afford good sites for the location of the outlet. When either one or both of the side slopes of the gorge are steeper than 2 to 1, this might lead to the slipping of an earthen dam constructed between them;

for this reason only a masonry dam should be built at such a site. If the gorge part of the dam is separated from the flank embankment by a hillock rising above the level of the top of the dam, or even its high-flood level, these portions of the work can be constructed independently of each other; the former might be designed as a masonry dam and the latter as an earthen one.

Another advantage of a ridge is that it provides facilities for the proper drainage of the dam which is of special importance for an embankment. The ridge should, however, not be very narrow, for, if it is, it may be liable to leak; may not allow space for the future raising of the dam, should that ever become necessary; and may also lead to greater cost and difficulty in construction.

Some engineers consider a ridge is an indication of former geological disturbance which may have fissured the strata and made them unreliable; careful geological examination is necessary to establish whether this is the case or not at the site under investigation.

(*c*) *The Waste Weir.*—For a masonry dam a proper site for a waste weir, although desirable, is not essential, since, where one does not exist, floods can be discharged over part of the crest of the work or through undersluices pierced in it.

For an earthen dam such a site is absolutely necessary, as on it the safety of the work depends. The best site is one separated by natural high ground from the flank of the embankment, so that floods passing over it will discharge clear of the dam. Such a site will be all the better if in longitudinal section it dips on both sides towards the centre to form a valley down the trough of which the floods will be directed in a confined channel. An inferior site is one at the immediate flank of the dam, and for some reasons a still worse site, one through the flank with the embankment on both sides of it. Special precautions must then be taken that the dam is not affected by the discharge of the waste weir; these will usually consist in building a protective lining wall on the side of the embankment and giving a cross-sectional slope to the tail channel away from the dam.

(*d*) *The Outlet.*—In a masonry dam the outlet can be placed where it will best suit the alignment of the canal from it. In an earthen dam consideration must also be paid to the safety of the embankment, for an outlet, although generally a necessity, may be a source of danger. The best site for an outlet under such a dam is at a small saddle, or depression, where the longitudinal slope of the embankment is fairly gentle, and especially when the saddle is remote from the river crossing; the earthwork will then settle equally on both sides to the outlet, and any subsoil percolation there may be will be directed to it and can be drained off, so that there should not be any chance of a slip. The worst site is on the steep side slope of a gorge, as there on the side next the stream the earthwork will tend to settle away from the outlet and the subsoil percolation to lubricate the base of the dam. If a deep saddle exists beyond the dam, that will form the safest site of all, as it will be independent of the embankment; it can be utilised by constructing either an ordinary outlet or a tunnel thereat.

(*e*) *The Reservoir Basin.*—The most capacious storage basins are cup-shaped in cross-section (i.e., the valley should have a flat bottom and steep side slopes), and have a wide waterspread near the dam, where the depth is at a maximum, and a gentle longitudinal ground slope. That slope can roughly be determined by inspection of the rapids and still reaches of the stream and the varying height of its banks. Generally, the best site for the reservoir will be where two valleys meet, and here probably the foundations for the dam will be good. The greater the mean depth of the reservoir, the less will be the loss from surface evaporation, but the greater will be that from absorption by the strata underlying the basin. The latter loss will usually be much the smaller of the two, and will tend to decrease as the bed gets covered with silt; to diminish it a retentive basin should be selected; a highly fissured basin should be rejected, as it will lead to great absorption, and may possibly endanger the safety of the dam, or lead to much loss of storage by underground leakage. Careful geological investigation of the subsoil conditions should therefore be made whenever there is any doubt of their reliability.

63. Storage.

(*a*) *General Remarks.*—(i) It is generally better to store the same amount of water in one than in several reservoirs, as this will usually reduce the cost of storage, the supervision of the works, and the loss by evaporation.

(ii) Reservoirs should, if possible, not be "in series," that is, one below the other, as the failure of an upper one may lead to the destruction of the lower ones, one after the other.

(iii) Where reservoirs in series cannot be avoided, their size should be regulated so that the lower a reservoir is the greater is its capacity, in order that it may be able the better to absorb the flood resulting from the failure of an upper one.

(iv) The storage capacity of a reservoir should be proportioned to and somewhat greater, say, 10 per cent., than the average yield of its catchment; it will thus be filled in all good years, will nearly fill in bad ones, and it will suffer proportionately less by its reduction by silting.

(v) The storage capacity should be sufficient for the irrigation of the irrigable area during the fair weather, but need not provide for the draw-off during the season of replenishment, if that consumption will be made good by subsequent inflow.

(vi) The amount of storage required depends upon the duty, or the rate of consumption (Art. 21) and on the extent of the irrigable area.

(vii) The culturable land in a reservoir basin should not exceed one-fifth of that which can be irrigated by the work, or the loss of revenue due to the submergence of the former will bear too large a proportion to that of the latter as increased by irrigation.

(*b*) *Computation of Storage Capacity.*—The calculation of the storage contents of a reservoir is made by summing up the contents between each of its contours. The formula to be used for this is:

$$Q=\frac{H}{3}\left(A+a+\sqrt{A+a}\right)$$

where Q is the storage in cubic feet;
A the area of a contour in square feet;
a that of the adjacent contour in square feet; and
H the vertical distance between the two contours in feet.

The vertical distance between the surveyed contours is usually 10 feet; to make the table of storage contents more correct it is best to interpolate by calculation intermediate contours 1 foot apart, and thus the contents at every foot will be obtained. The calculation is made on the assumption that the square roots of the areas of the interpolated contours between those of the surveyed ones are in arithmetical progression. The table should commence at outlet sill level, as the storage below that is ordinarily not available for irrigation.

(*c*) *Definitions of Storage Capacities.*—The "gross storage capacity" of a reservoir is its total contents above ground level; its "gross available capacity," that above outlet sill level; and its "net available capacity," the latter amount less the allowance for all losses; it is on this smallest quantity that the irrigating capacity of the storage depends.

64. Silting.

(*a*) *Factors of Silt Production.*—Reservoirs are liable to have their storage capacity reduced by the deposit in them of silt derived from their catchment; in the worst cases the reduction is very considerable. The amount of silt depends upon the extent of the catchment area, the nature of the surface soils, and climatic conditions. Soils which disintegrate under the action of the weather or are soluble produce the most silt; the climatic conditions leading to the production of silt are frost, intense heat and dryness, and violent downpour of rain scouring the ground. Every drop of water brought down by the floods contains some silt; to reduce the rate of silting up, it is therefore necessary that the catchment area should not be excessive, *i.e.*, should be only sufficient to fill the reservoir to slight excess in an average year, or, conversely, that the storage capacity should be about equal to the average annual yield. Also, the nature of the surface catchment should be such as will not produce much silt. More silt is produced by steep slopes, bare or tilled surfaces and friable or soluble soils, and less silt by gentle slopes, surfaces covered by vegetation, especially grass and trees, and hard or insoluble soils. In the tropics most of the silt is washed down by the first heavy storms which carry off material loosened by a long period of drought when the temperature is high.

(*b*) *Classification of Silt.*—The deposit in reservoirs may be divided into three classes:

(i) Heavy detritus, consisting of stones, pebbles, and large sand; this is kept in suspension only as long as the water is in motion, and is deposited as soon as the velocity is much checked.

(ii) Heavy silt, consisting of fine sand and coarse earthy matter; this remains in suspension for some time after the motion of the water has ceased.
(iii) Fine silt, consisting of flocculent earthy matter, which stays suspended in mechanical solution, the bulk of it for a long time, and all of it for several days. Only this kind has manurial value.

Owing to its physical condition it is difficult to remove silt by mechanical means, and the cost of such removal is generally prohibitive. The best arrangement therefore is to pass the first heavily-charged floods out of the reservoir by means of undersluices of large discharging capacity, and to impound only the subsequent clearer flows.

65. Losses of Storage.

(*a*) *Evaporation and Absorption.*—Stored water is lost by evaporation (Art. 17) from the surface of the reservoir and by absorption (Art. 18) by its bed; in the latter loss is included that due to leakage under the dam. In India the daily vertical loss by evaporation is greatest in the hot weather when the air is hot and dry and the wind strong; then, however, the surface area is at a minimum. That loss is smallest in the cold weather when the air, although dry, is cool and the wind is light; then the surface area is nearly at its maximum. In the monsoon the high winds cause much evaporation, but the virtual loss is reduced by the rainfall on the reservoir, as the whole of this, and not only a portion of it due to run-off, is absorbed by the storage. The vertical loss by absorption is at a maximum in the monsoon, when the reservoir is at its greatest depth and its water exerts most infiltering pressure; it is at a minimum in the hot weather, when the depth and consequent pressure are least. Generally, the loss by absorption is much less than that by evaporation.

In reservoirs it is practically impossible to measure these losses separately, and they are therefore usually taken together. The allowance made for them in Bombay is generally a quantity equal to the mean area of the reservoir multiplied by 4 feet, which, as the surface is continually diminishing in the fair season, and the effect of rain falling on that surface is neglected, is practically equivalent to a total depth of about 6 feet on the different areas exposed throughout the year. The depth of 6 feet may be taken as equal to a monthly loss of 3 inches in the cold weather, 9 inches in the hot weather, and 6 inches in the monsoon, each season being assumed to last four months. The earlier the contents are reduced by being drawn on for irrigation, the less will be the total combined loss. Owing to the amount of this loss, water should not be stored in irrigation reservoirs for more than a single season, or much will be wasted.

(*b*) *Silting.*—What may be considered to be a capital loss of storage is that due to the silting of the reservoir (Art. 64). The amount of this will have to be determined by experiment in each reservoir, but it should not exceed annually $\frac{1}{1500}$ of the full-supply contents of the reservoir. As the contents are thus decreased year by year, so also will be the total loss of storage on this account, and there will also probably be a saving of loss by absorption due to the puddling of the basin by the deposit. The chief objection to silting is that it continually decreases the capacity of the reservoir, whereas the demands of irrigation on it should constantly be increasing. The most effectual remedies are to reduce the rate of deposit by passing the earlier heavily silt-laden floods out of the reservoir, and, when the capacity is sensibly diminished by silting, to restore it by raising the full-supply level of the storage.

66. Cost of Storage.

The cost of a reservoir generally exceeds considerably that of the canal and distributing works in connection with it. It is therefore necessary to reduce the expenditure on the former to the minimum practicable by careful selection of its site. The following would be considered fair rates for storage in Bombay for reservoirs with earthen dams; if they are greatly exceeded in a project under contemplation, it may be necessary to abandon it:

	Million Cft.	Rs. per Million Cft. Available Capacity.
Small reservoirs storing less than ..	200	750
Medium reservoirs storing from	200–1,000	500
Large reservoirs storing more than ..	1,000	400–300

So few reservoirs with masonry dams have been constructed there that a similar statement cannot well be made for them but, roughly, their storage rates may be taken as about one-

and-a-half times those for works with earthen dams. The cost of such works is much affected by the nature of their foundations.

Although a truer comparison of the cost of storage would be made by taking into account the net available capacity rather than the gross available capacity (Art. 63 (*c*), the latter is adopted, as the former varies with the way in which the water is expended (Art. 65).

Before a project is drawn up in detail, it is advisable to ascertain roughly what will be its storage rate. The cost of a reservoir depends chiefly upon that of the dam, and this can be estimated approximately and quickly from its longitudinal section. Judging from twenty completed works with earthen dams of various sizes in Bombay, the cost of the outlet, waste weir, and land compensation should not exceed 30 per cent. of that of the dam. The approximate total cost divided by the storage capacity will give the rough storage rate. If this is favourable, the next step to take is to ascertain by rough estimates the approximate costs of the other parts of the reservoir. From the Bombay examples quoted these should not greatly exceed the following percentages of the cost of the dam—outlet, 7 per cent.; waste weir, 12 per cent.; and land compensation, 9 per cent. If any sub-work proves excessive in cost, it should be seen if another cheaper site is available for it, or whether the reservoir as a whole can be designed more economically.

67. Expenditure of Storage.

The consumption of water from a reservoir should be regulated as carefully as the expenditure of money, for otherwise the storage may not suffice until the subsequent replenishment restores it, and the duties and revenue expected from the supply may not be realised. For this purpose an estimate of the expenditure of storage should be prepared beforehand. Assumptions should be made from experience of previous results of the acreages to be irrigated during the different seasons, and of the average duties to be allowed. The level of the reservoir due to the consumption should be calculated month by month, and from it should be deducted an allowance for evaporation and all other losses. The levels thus determined should not be reduced in actual working without due authority. The starting level should be the actual one at the end of the replenishment, and the calculated closing level should allow for a small balance in the reservoir to provide for a delayed replenishment in the following year.

68. Temporary Storages.

(*a*) *General Remarks.*—Reservoirs which do not impound water for prolonged supply may be classed as "temporary storages"; they may be used for one or other of three purposes—flood-regulation, assistance to irrigation, or as stands-by for town water supply and power and lighting schemes, and they may be formed either by masonry dams or earthen embankments. In the first two cases the storage capacity can generally be limited to the probable amount of floods following each other in rapid succession, as thereafter the reservoirs will be emptied to receive the discharge of similar subsequent floods, so as to impound them also temporarily. To enable them to do this, they must have sufficient outlet discharging capacity to run off their contents during the intervals between floods. They should, however, also have waste weirs or auxiliary sluices able to discharge floods arriving when the reservoirs are full or nearly so.

(*b*) *Flood-regulating Reservoirs.*—This class will probably be required on comparatively large streams, the uncontrolled floods of which are causing extensive damage either to towns or agricultural tracts. Properly to regulate such floods the capacity of the reservoir should be so great that it will never attain high-flood level, for, should it rise thereto, its utility will largely be decreased as the high-flood discharge will pass through the reservoir at an undiminished rate, but even then its duration will be reduced. If floods succeed each other in rapid succession, a very large outlet will be necessary, and this can best be formed in a masonry dam. Preferably the outlet sluices in such a dam should be grouped together, so as to shorten the length of the section in which they will be placed, for that section will have to be thickened to allow for the voids produced by the sluices. This grouping will also tend to maintain a definite scouring channel through the reservoir, and will thus diminish the deposit of silt in its bed. When the water is not to be utilised, it is not necessary to regulate the discharge from the outlets, and therefore sluice gates are not required for them, as they can be left constantly open.

If, however, the reservoir is on a tributary stream, it may be desirable to impound its contents while the main river is in high flood, and to discharge them after that has decreased; in this case sluice gates will be required. The sills of the sluices should be placed at a level above that of the high flood of the river downstream, as if they were lower their discharge would not be much increased while that flood lasted, but would be greater during the intervals between floods, and would then have more destructive force on the masonry of their vents; they would also cost more to construct and require more power to work. For an earthen dam the outlet sluices should be placed at one or both sides of the impounded river, so as to get good foundations at the proper level; for a masonry dam they can be located vertically above the river bed, in which case it will be best to build a water-cushion weir below them to protect the foundations.

A masonry dam can be constructed where there is not a site for a waste weir, as the balance of the high-flood discharge can be passed out through a series of upper sluiceways, or over a lowered section of the crest; these should preferably be vertically above the river, which, when in flood, will act as a water cushion to them. The objection to this treatment is that the downstream face of the dam may be injured by that discharge. For an earthen embankment a waste weir is essential, unless the contents of the storage of the reservoir are made considerably greater than the probable total amount of a succession of high floods, and even then breaching sections (Art. 83 (*g*)) will be necessary to safeguard the main part of the dam.

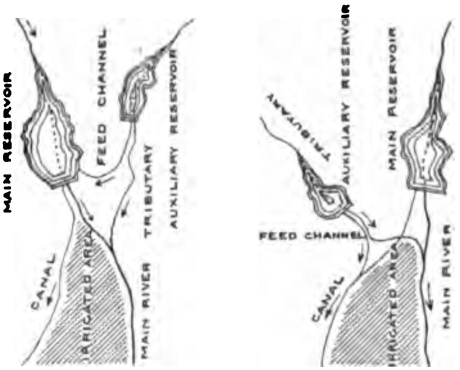
(*c*) *Auxiliary Reservoirs.*—Occasionally it may be necessary to supplement the storage of a main reservoir by constructing an auxiliary reservoir which will divert the yield of a neighbouring catchment into it, or utilise that yield by providing supply to the canal system direct for a short time (Fig. 19). In the former case the outlet sill of the auxiliary will have to be placed at a level to enable it to feed the main reservoir when that is full or nearly so, and in the latter at one which will command the irrigable area. The discharge of the outlet may be made much less than that of a flood-regulating reservoir, as it need not exceed the storage contents divided by the considerable time between replenishments which may be taken into account; should a subsequent flood arrive earlier than anticipated when the auxiliary reservoir is nearly full, it can be passed off by the waste weir. When a supply channel has to be led from the auxiliary to the main reservoir, it can thus be made of a small section; its minimum discharge need only be about the average flow throughout the flood season of the yield of the catchment.

The outlet will have to be provided with sluice gates, so that the discharge of the vents may be regulated as desired.

The full-supply contents of the reservoir need not exceed the anticipated yield divided by the number of times the storage is expected to be filled and emptied in an average year. It is desirable that the auxiliary should be full at the end of the season of replenishment, as this will reduce the rate of cost of the total storage of the system to a minimum, and will also increase the water available for irrigation. For this reason a waste weir will be necessary, and, as explained above, its provision will enable a reduction to be made of the storage capacity of the auxiliary and of the size of the feed channel to the main reservoir.

FIG. 19

AUXILIARY RESERVOIRS


SUPPLYING RESERVOIR SUPPLYING CANAL

(*d*) *Stand-by Reservoirs.*—The necessity for these for power and lighting schemes has been described in Article 44; they are similar to auxiliary reservoirs, and may similarly be placed upstream of the power, etc., station, or the intake of the irrigation works, as the case may be.

69. Supply Channels.

(*a*) *Simple Feed Channels.*—Occasionally the natural catchment is not sufficient to fill a reservoir, and has to be increased artificially by running supply or feed channels to lead part of the yield of the neighbouring drainage areas to the storage. In the simplest form these channels merely intercept part of the run-off of the rainfall from the ground upstream of them. The rate of this run-off is an extremely variable one, being small during light and medium showers, which may occur frequently, and great in heavy downpours, which, although they happen seldom, produce the bulk of the total annual yield. If the cross-section of the channel is designed to carry only the discharge of the former, it will be insufficient to convey much of that of the latter ; if, however, it is increased to pass down a large fraction of the latter, it will have to be considerable in size and expensive, and there will be much loss of transit during small flows. A compromise has therefore to be made and a section adopted between the two extremes ; this might be made sufficient to deal with, say, one-eighth of an ordinary heavy run-off. It will thus intercept most of the lighter discharges, and might on the whole be estimated to pass one-quarter of the total yield into the reservoir, so that the "equivalent catchment" which it adds to the natural one of that storage might be taken as one-quarter of its own drainage area. Such simple channels are liable to breach during heavy storms, and thus to lose much supply, and to silt extensively, and thus cost much to maintain.

(*b*) *Feed Channels with Auxiliary Reservoirs.*—A superior form consists in making small auxiliary reservoirs where the line of the supply channel crosses watercourses. These will impound the bulk of the run-off of even heavy rainfall, and this can be passed to the main reservoir at an average rate in a channel of small size less subject to silting. Moreover, should the channel breach, the reservoir can be shut off until repairs are effected, and loss of yield will thus be avoided. These advantages will usually have to be paid for by the increased cost of the system.

(*c*) *Supply Channels from Large Streams.*—The best form of supply channel is one led to the reservoir or to feed the irrigation canal directly from a stream with long-lived flow. Its capital cost will probably be a maximum one, although the expense of the intake weir headworks will virtually be reduced by the saving resulting from a supply channel smaller in section and shorter in length than an ordinary one. Practically the stream itself forms part of the course of the supply channel, and this extension is a valuable one, for being in a valley it receives drainage from both banks. The cost of maintenance should be the cheapest, and the certainty of supply the greatest of all forms of supply channel. The longer the discharge of the stream is sufficient to fill most of the section of the channel, the more may the capacity of the reservoir be reduced. Even a small storage in such a combination may be of great utility, as it may permit of the irrigation of a large area of perennial crops which the unaided stream could not bring to maturity.

(*d*) *Main Supply Canals.*—In Ceylon there are some large ancient supply canals which work in a reverse way. They start from very large reservoirs constructed in the area of abundant rainfall and feed minor tanks, which being situated where the rainfall is uncertain, have otherwise a precarious replenishment. These old tanks, however, occupy much valuable land, reduce by their storage the amount of fertilising matter in the water, increase the loss by evaporation, and cause malaria in the villages near them. It may thus often be advisable to cut them out from the system, and supply their commanded areas and reclaimed beds directly from the main reservoir at the head (Art. 99 (*b*)).

(*e*) *General Remarks.*—A supply channel should enter a reservoir above its full-supply level so that the discharge of the inflowing water may not be interfered with when that level is being attained. Moreover, the channel should have its outfall above the high-flood level of the reservoir when there is any likelihood of the storage being subsequently increased. Supply channels, being intended to feed reservoirs, should not have their discharge utilised for irrigation *en route;* the generally fluctuating character of their flow is also against such a practice.

CHAPTER VI.

MASONRY DAMS.

70. Masonry Dams compared with Earthen Embankments.

(*a*) *Advantages.*—The advantages of masonry dams are:

(i) They can safely be constructed across gorges with very steep side slopes, whereas such slopes would tend to make an earthen embankment slip.

(ii) They can be built at sites where waste weirs cannot be formed; in such cases floods can be discharged over a lowered part of the crest or through undersluices.

(iii) It is easy and comparatively cheap to have in them numerous and large undersluices to pass off the earlier heavily silt-laden floods, and thus to diminish the rate of silting of the reservoir.

(iv) The failure of a masonry dam is not likely to result in such disaster to life and property as that which would probably happen from the destruction of an earthen embankment.

(v) Masonry dams can be built of greater height than earthen ones.

(vi) Masonry dams are more suitable than earthen ones where the rainfall is excessive; the latter are, however, feasible there as the local earthwork will be able to withstand the downpours, or would otherwise have been denuded.

(vii) The maintenance of a masonry dam is not so expensive as that of an earthen one.

(*b*) *Disadvantages.*—The disadvantages of masonry dams are:

(i) Only the soundest rock foundations are permissible; any defect therein is likely to cause the dam to fail.

(ii) The expense of the construction of a masonry dam generally exceeds greatly that of an earthen one. This will especially be the case where the foundations are deep; in a masonry dam such will entail the building on the low foundations of a wide section for a considerable height, whereas similarly to render an earthen embankment secure only the comparatively narrow puddle trench will have to be deepened.

(iii) The construction of a masonry dam takes a long time.

(iv) A masonry dam requires a large amount of skilled labour, and it is therefore not so suitable as an earthen one for providing work for famine relief purposes.

Generally, it may be said that a masonry dam is safer than an earthen one when the depth of water impounded exceeds 80 feet, and that it is advisable to adopt the former for deep storages for town water supply.

(*c*) *Selection of Kind of Dam.*—Although earthen embankments can be safely constructed, it is the fact that there have been more accidents to them than to masonry dams properly designed and built. A masonry dam should therefore be preferred where there would be any risk incurred by having an earthen one, especially when the security of the storage must be assured at all costs, as for a town supply. A masonry dam is peculiarly adapted to a site having a gorge with steep side slopes and high flanks, with good foundations near the surface. The fact that the locality of the dam is subject to extremely heavy rainfall should not, however, preclude the construction of an earthen embankment, as at such a place the earth available will generally be found suitable to the local conditions, and anyhow it can be protected from the weather by a good casing on the downstream slope. Naturally, the amount and cheapness of the materials procurable will greatly influence the selection of the kind of dam to be built.

(*d*) *Alignment of Dam.*—The alignment of both forms of dam should be in as few straight lines as possible, so that the appearance of the work may be in keeping with its scale. Following minutely the irregularities of the ground will not as a rule effect much saving compared with a carefully selected equalising line. These straight lines should be united by curves, which in the case of masonry dams should, for the sake of appearance and on account of the downstream batter, be bold; in that of earthen dams the curves may be shorter to save trouble in setting out.

71. Conditions to be Satisfied by Design.

In order that a masonry dam should be designed stable, the following conditions should be satisfied at the foundation and along any horizontal section, whether the reservoir is full or empty:

(i) The intensity of the maximum compressive stress at the extreme points of the section shall not exceed the safe limit of resistance of the material of the dam or of its base. (This condition implies there will not be any failure by settlement or crushing.)

Note.—Where the section batters, this stress does not act vertically, and its intensity is increased beyond that which occurs when the face is vertical. The amount of increase is indeterminate, so the usual practice is to allow for it by taking a smaller working intensity for the downstream face.

(ii) There shall not be tensile stress at any point of the section. (This condition is fulfilled when the line of resistance lies within the middle third of the section, and when it is satisfied, there is not any possibility of the dam overturning.)

(iii) The resistance to shearing, or sliding, shall be greater than the total horizontal force acting on the section.

The design assumes that the dam will be practically impermeable, and will be constructed with sound and suitable materials and by good workmanship; it neglects the vertical component of the water pressure on a battering part of the upstream face, thus introducing a small factor of safety. It is best for the design to be made by the graphic method, so that the designer may see at each step what he is doing.

Recently the theory[1] has been advanced that the critical sections of a dam are the vertical and not the horizontal ones, and that a work collapses first by tension on the vertical sections of its faces, causing them to shear, and this is continued by tension on the foundation, causing the dam to lift from its base. This opinion has been opposed by leading engineers, who state that the dam problem cannot be solved by pure mathematics. They point to the fact that, owing to the factor of safety allowed, dams designed so as to fulfil the conditions just stated have all stood, and that the few which have failed have done so because they have not complied with those conditions. Special precautions, however, seem necessary to prevent tension acting at the upstream toe from causing a fracture, which would allow water to enter and buoy up the dam.

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[1] Minutes of Proceedings, Inst.C.E., Vol. CLXXII., Paper No. 3,765.

The experiments on which the theory was based show that the rock foundation is stressed more severely than the masonry superstructure, and indicate that the work should be founded only on the soundest rock.

72. Modifications of Ordinary Design.

(*a*) *Tension at Upstream Toe.*—To avoid tensile stresses at the upstream toe the following proposals have been made :

(i) To bring the centre of gravity of the section of the dam nearer to the upstream face, by making the upstream face vertical (Art. 34), or by increasing the free-board, or by widening the top of the dam at the coping.
(ii) To increase the section of the dam generally.
(iii) To back the dam on the downstream side with embankment, in order to secure normal, or nearly normal, counterbalancing pressure on that side.

The masonry at the upstream toe should consist of the largest blocks possible, so as to reduce the number of joints. Bonding the dam on to its foundations by iron rails, uniting both, has also been suggested, but does not seem advisable, as the metal may rust, expand, and finally deteriorate. Good natural bond is, however, most desirable.

(*b*) *Permeability and Drainage.*—Water from the reservoir entering the upstream face of the dam will tend to buoy it up, thus decreasing its weight and stability (Art. 78 (*a*)), but in masonry the effect is so small that it is neglected in the theoretical calculations. It is, however, desirable to reduce even this amount of penetration, and that can be done by pointing the joints or plastering the face with cement. It has indeed been proposed that the water should be prevented from having direct access to the face of the dam by forming slabs of reinforced concrete some distance in front of it, with a vacant and drained space between, which will be of use for inspection purposes. It seems necessary to take special precautions to prevent infiltration at the base of the dam, and these might consist of a deep cut-off trench a little upstream of the upstream toe filled with fine cement concrete, and a cover of the same material extending over it to that toe into which it would be keyed.

Despite all precautions, many dams allow a small amount of water to percolate through them, and percolation into them under great pressure may also take place from the natural high flanks of the valley. In the Vyrnwy Dam [1] a system of internal drainage was therefore provided to deal with this. A longitudinal tunnel 4 feet 3 inches by 2 feet 6 inches was constructed on about the centre line of the dam, with its sill above the downstream backwater level, and along the base of each of the more important foundation valley beds of the rock (not within 15 feet from the faces of the dam) a drain between 6 and 9 inches square was built, and was connected by a vertical branch drain with the tunnel. The drainage collected by the tunnel was discharged out of the dam by a cross tunnel; it has always been very small in amount, and fluctuates very slightly.

(*c*) *Temperature Stresses.*—The variation of temperature, especially near the thin top of the dam, produces great stress on the masonry, and in works constructed with cement has caused cracks to form on the face; but these should not extend to any great depth in the wall, as its hearting does not vary much in temperature. Cracks on the upstream face are, however, undesirable, as they admit water which tends to buoy it up. It has therefore been proposed to bury iron rods in the top of the dam—if cracking is prevented there, it is not likely to start lower down. The better course, however, appears to be to use elastic hydraulic lime rather than rigid cement in the construction; the slow setting of the former also allows initial strains to adjust themselves. A curved dam has an advantage over a straight one in resisting by its elasticity the effects of temperature changes.

(*d*) *Effect of Weight of Masonry.*—It is usually considered that the weight of the masonry affects the design of the profile of a dam, but Sir Guilford Molesworth has pointed out [1] that between the limits of 135 and 150 lbs. per cubic foot the weight had little influence, for although heavier masonry generally caused increased pressure on the base, the resultant pressure was thereby moved nearer to the upstream face, and there was thus not a greater maximum pressure on the dam. Heavy masonry theoretically entails slightly increased dimensions on the upstream face; light masonry might affect the resistance to sliding. In preliminary calculations, when the weight of the masonry is between the limits mentioned, it is convenient to take it as two and a quarter times the weight of water, that is, as 140·6 lbs. per cubic foot. It may be noted that when the water is silt-laden, that fact should be taken into account in calculations; in Gwalior, Central India, such water has been found to weigh from 64 to 66·6 lbs. per cubic foot instead of 62·4 lbs., the weight of clear water.

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[1] Minutes of Proceedings, Inst.C.E., Vol. CXXVI., p. 30.

73. Details of Construction.

(*a*) *Foundations.*—As pointed out at the end of Article 71, dense unfissured and solid rock is most desirable for the foundation which must, anyhow, be superior to the masonry to be built on it. To test that the rock is suitable, the prepared bed should be struck forcibly with a sledge hammer, which should rebound with a clear ringing sound, and all shaken parts should be removed; trial pits should be excavated in it for some depth to see that the character of the sub-rock is sound. Particular care is necessary to fill all fissures; large ones should be excavated out and filled with cement concrete or masonry, and small ones grouted with cement under pressure. All springs should be carefully dealt with (Art. 42). Smooth rock should be roughened generally, and longitudinal key trenches excavated in it. At the toes it is advisable to dress the rock with slopes downwards to the centre line; the central part should, if practicable, be roughened in horizontal steps so as to secure proper bedding and keying, and so as to prevent creep of water.

In some formations such as the Deccan trap, joints and fissures extend to a great depth, although the rock is amply strong. The practice in Bombay is to excavate the foundations to the full width of the deepened section and for a considerable depth (depending on the pressure head and the nature of the strata), and to construct the masonry from this lower level so as completely to fill the excavation, and thus to unite it solidly with the rock on each side of it, which for this reason is left undisturbed. Even if there is then upward pressure under the base of the dam, it does not matter, as this part of the work forms a mass continuous with the rock which extends on each side of it for a great length, and thus also it can neither slide nor overturn.

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[1] Minutes of Proceedings, Inst.C.E., Vol. CXV., pp. 84–87.

(*b*) *Masonry.*—The superstructure must be water-tight, and horizontal cracks or planes must not exist in it, otherwise water will permeate through the work and lessen its weight and stability. Brickwork is therefore out of the question for dams of any height, and coursed masonry or ashlar for dams exceeding a moderate height; for large dams the masonry should be uncoursed, and should break joint in all directions, and each stone should have clean irregular surfaces, and should be solidly built in and bedded on stiff mortar without grouting. In order to resist vertical and horizontal shear building stones derived from stratified rock or in good blocks should, near the face of the dam, be built with their beds alternately parallel and at right angles to that.

For the sake of appearance dams are often faced with heavy coursed masonry, which increases their strength there, but interferes with the homogeneity of the structure. Such facing should consist of large stones so as to reduce the number of joints, and should be carefully bonded with the hearting to prevent separation; on the upstream side it should be pointed or plastered with cement to make it as water-tight as possible. In Bombay dams are built with a downstream casing of block-in-course facing backed with coursed rubble masonry (or this may consist of coursed rubble masonry throughout), and an upstream casing of coursed or rough-coursed rubble masonry; these facings vary from 1 to 3 feet in thickness. The hearting consists of uncoursed rubble masonry; in the upper part of the dam, where the pressure does not exceed 60 lbs. to the square inch, for this is generally substituted concrete with large "plums" or stones embedded in it.

(*c*) *Concrete.*—Concrete can be used in the upper part of the dam, so as to effect economy in cost without loss of stability and water-tightness; to ensure these qualities it must have its ingredients carefully proportioned and mixed, and must be consolidated free from all vacuities. To increase the weight of the concrete and to bond its layers together rough stones known as "plums" as large as can be handled, are laid in the work; near the faces they should be placed with their longer dimension roughly parallel thereto; elsewhere they should be laid to break joint in every direction. They should be bedded full in mortar, should be malleted down on to their beds, and their tops should project into the upper course. The concrete should be rammed tightly on to their sides, which should first be coated with mortar to secure thorough union.

74. Raising Masonry Dams.

(*a*) *Method employed at Assuan.*—Until recently high masonry dams had not been raised to any extent beyond their originally designed height and this was a disadvantage compared with the advantage possessed by earthen dams in the facility with which they could be increased. The Assuan Dam is a modern instance of the feasibility of heightening a masonry dam. There the new downstream facing was built with courses normal to the old profile, and was separated from it by a space, which, after the lapse of two years, was filled with concrete aggregate grouted with cement. During construction the two parts were held together by iron rods embedded in each. This design was adopted so as to secure the equality of the temperature of the two masses of masonry before they were united. Arrangements were made for utilising permanently as drains the horizontal pipes fixed for testing the progress of the grouting of the joint.

(*b*) *Suggested Method.*—Owing to the slow rate of construction, it would seem that the thickening section added for the raising of the dam would have plenty of time in which to acquire the same temperature as that of the old masonry. More important considerations appeared to be connected with the settlement of the new work, the effect of the new work on the stability of the old work when the reservoir became empty, and the prevention of infiltration between the two masses of masonry. With regard to settlement it would seem desirable to construct the new work at a vertical rate not exceeding 30 feet in a year, and after it had attained the level of the top of the old dam, to allow a year to elapse before adding the new crest over both.

The effect of building the new work in courses normal to the steep face batter of the old work and not bonded to it, would, if the mass of the raising were great compared to that of the original dam, be to give the former a tendency to overturn the latter when the reservoir was empty. It would therefore appear better to follow the ordinary method of construction of additional masonry by building the thickening in level courses and level stages continuous throughout the dam, starting from the lowest part of its base. When there is a probability that a dam will have eventually to be raised, it would be advisable, in order to secure the proper bonding of the new work with the old, to build the original downstream face with a stepped and not a curved profile, and at intervals with vertical dovetailed recesses and projections.

(*c*) *Prevention of Infiltration.*—To prevent infiltration it would seem best to coat the old face with mortar and to build the new one tightly abutting against it. To deal with any water which might find its way into the joint between the two, longitudinal drainage and inspection culverts might be built at vertical intervals along the junction, with cross outlet culverts at horizontal intervals to drain them. The former would tap all infiltration water met with at their level, and intermediate water would probably disclose its existence by dripping into them. These longitudinal culverts would thus enable any subsequent repair found necessary to be carried out at minimum expense, and to be localised to really defective parts of the junction between the new and the old work.

75. Curved, Buttressed, and Reinforced Concrete Dams.

The previous Articles apply to "gravity" masonry dams which are designed to resist the pressure of water solely by their weight, but there are other kinds of masonry dams—curved and buttressed—and dams of reinforced concrete in which the disposition of the material is arranged so as to resist the forces acting thereon by greatly reduced mass.

(*a*) *Curved Dams.*—When a dam is built to a curve it resists the action of water pressure, partly as a cantilever beam, and partly as an arch. If the dam is a long one, its arch action will be small, and will not justify the extra expenditure incurred in the attempt to secure it. If, however, the dam is a short one, the arch action will be considerable, and if allowed for in the section, will conduce to economy; such a dam will transmit much pressure to its abutments, which must therefore be quite sound. It would not, however, be safe to take both beam and arch action into account so as to obtain a section of dam slighter than would be designed for only one such action, as the variations in length of the dam from top to bottom, in thickness and in construction, introduce insoluble difficulties in calculation. The curvature of a dam also causes practical difficulties and extra expense in construction, so that this form of alignment seems suitable only for short dams; it is, however, considered by some to give long dams more elasticity to resist the effects of changes of temperature. In New South Wales[1] several curved dams of slight section have been built comparatively recently and economically with maximum heights of from 32 to 87 feet, on the assumption that the masonry may be calculated as part of a ring, not an arch. This assumption appears erroneous, as when a complete rigid cylinder is subjected to external pressure its form remains circular, although its diameter is diminished, and the distribution of pressure is similar on all of its cross-sections. When, however, only a segment of a cylinder is under external pressure and its ends are practically fixed at the abutments, the internal curve of pressure will not be parallel to its bounding surfaces, and the distribution of pressure will be much more unequal on the cross-sections nearer the abutments than on those more remote from them. In this case the segment really becomes an arch with fixed abutments, and the determination of the stresses becomes so complex as to be almost incapable of solution. The complexity is increased by the fact that, as the base is immovably held by the foundations, only the top part is free to act as an arch. The success of these not very high dams seems therefore due to the factor of safety allowed in the calculation of their sections.

(*b*) *Buttressed Dams.*—This form of dam has been proposed with a view to obtaining economy where the length of the work is considerable, and is thus not suitable to a single arch alignment. It consists of a series of piers, or buttresses, between which thin arches are constructed, and each buttress has to resist the stresses produced by the water pressure on the halves of the arches abutting against it. The design effects a saving of material, but it is doubtful if one of cost results, as the thin masonry will be of an expensive character. It has to be remembered that the weight of the dam has to be borne by the foundations, and that the pressures on them and the masonry must not exceed safe limits so that a very thin arch is not permissible. A thin arch will have a narrow foundation, and both may thus not be wide enough to prevent infiltration of water. Moreover, the future raising of such a dam would be difficult. For these reasons the design has not met with much favour.

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[1] Minutes of Proceedings, Inst.C.E., Vol. CLXXVIII., Paper No. 3,791, by L. A. B. Wade, M.Inst.C.E.

(*c*) *Reinforced Concrete Dams.*—Reinforced concrete dams have been constructed only recently and chiefly in America; lengthy experience has therefore not yet been gained how the material behaves under the long-continued action of water at high pressure, and until it has been obtained, it does not seem advisable to construct high dams of this type. Another objection to reinforced concrete dams is that apparently they cannot be raised except perhaps at great cost. Such dams consist of a series of nearly triangular-shaped buttresses supporting between them on their upstream face flat slabs of reinforced concrete. The buttresses have to be designed like masonry dams to carry the whole water pressure on the two half spans on each side of them; they must be very securely founded, and to distribute the pressure on their foundations it is advisable to construct them with wide reinforced concrete footings. The slabs have to be impermeable, and should therefore be made with stiff mortar; their thickness and reinforcement at different levels should be proportioned to the pressure they have there to sustain. To guard against cracking due to variation in temperature there should be a reinforcement of temperature and distribution rods, or of a mesh of expanded metal. The slabs can be laid separate from or continuous with each other—the latter seems the better arrangement for securing water-tightness. In non-continuous slabs the downstream face is in tension, and the reinforcement is placed near that face, and thus as far as practicable from the water; in continuous slabs the upstream face is in tension over the buttresses, and the reinforcement has to be formed near that face, and to be protected by a sufficient thickness of concrete. Taking the dam as a whole, its wide base and the weight of the water on the gently inclined surface of the slabs increase its resistance to overturning, and compensate for the lightness of its general section. An advantage of this type is that the whole work can easily be inspected. The nature of the construction requiring specially skilled labour and much supervision is against the adoption of this form in backward countries.

Reinforced dams have been founded on hard soils, and then deep cut-off walls are required at the upstream toe; on such foundations only low works are advisable, and, as it is, accidents have occurred. They have also been made into overfall weirs by the construction in addition to the upstream sheeting of a downstream one of reinforced concrete, with a few holes in it to prevent the formation of a vacuum between the two faces by the action of the flowing water.

CHAPTER VII.[1]

EARTHEN DAMS.

76. Kinds of Earthen Dams.

AN ordinary earthen embankment may be formed in one of the following ways, with—

(i) A puddle wall at the centre, or on the water slope, or in some intermediate position;
(ii) A clay hearting supported on each side by more stable material (this hearting is practically a very thick puddle wall of material inferior in water-tightness to puddle);
(iii) A homogeneous section without a puddle wall.

In English practice (i), with the central puddle wall, is the type generally adopted; in recent practice in Bombay (ii) has been followed; while the earlier dams there were constructed of black "cotton soil" throughout according to (iii), which, with the important modification of these examples described in Article 87 (*b*), is the type now recommended and dealt with in this chapter. In America several kinds of "rock-fill" dams have been constructed for comparatively low heights, but for greater ones "hydraulic-fill" dams and dams with masonry core walls are there preferred to all other types. The two last-named are described in Articles 80 and 81.

77. Theoretical Matters.

(*a*) *Deficiency of the Theory of Earthwork.*—Properly designed and constructed earthen dams are amply sufficient to withstand the pressure of the water which they hold up. The only way water can and does act prejudicially against them is by infiltration, which diminishes their frictional resistance and adhesion. There have been many mathematical investigations as to the behaviour of earthwork, but these have been based on laboratory experiments, in which it was treated as a homogeneous material, and they did not take into account the variations in the soils and in construction which occur in practice. These experiments are, however, most useful in indicating the nature of the forces at work, although they cannot demonstrate their actual intensities. With respect to earthen dams, engineers therefore prefer to be guided by experience rather than pure theory, and they are supported in this view by leading investigators. Mr. (since Sir) G. H. Darwin,[1] M.A., F.R.S., concludes: " The soundest view seems to be that engineers have no better practical course open to them than, neglecting the elaborate formulas which have been suggested, to work with semi-empirical rules, such as those of Coulomb, and to allow a large coefficient of safety." Professor Rankine [2] has stated: " There is a mathematical theory of the combined action of friction and adhesion in earth, but for want of experimental data its practical utility is doubtful."

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[1] This chapter is chiefly an abridgement of "Indian Storage Reservoirs with Earthen Dams," second edition, Spon & Co., by the Author.

(*b*) *General Causes affecting the Stability of Earthwork.*—Earthwork gives way by the slipping, or sliding, of its parts, as they are not in rigid connection with each other. The resistance to this motion is due partly to the friction between the particles, and partly to their mutual adhesion or cohesion.

The friction [3] is measured by the angle of repose, and constants for it for different soils have been determined; these are coefficients of the weight of the mass. Friction is greatest for coarse and least for fine soils; on it depends the permanent stability of natural earthwork. A slight addition of moisture increases the coefficient of friction, but an excess of water acts as an unguent in diminishing the friction.

The adhesion, or cohesion, may be measured by the depth to which an unsupported face of earthwork will stand before that is affected by the weather; it gives additional stability to earthwork. It is an extremely varying force; it is increased by a moderate amount of moisture, but is diminished by excessive wetness.

It is therefore evident that any given earthwork, other things being equal, will be most stable when slightly damp, and least stable when charged with water. Hence its stability depends upon the facility and thoroughness with which it can be drained of superfluous and dangerous water.

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[1] Minutes of Proceedings, Inst.C.E., Vol. LXXI., p. 378.

[2] " Civil Engineering," eleventh edition, p. 324.

[3] *Ibid.*, pp. 315, 316.

Professor Rankine[1] sums up the matter thus: "The properties of earth with respect to adhesion and friction are so variable that the engineer should never trust to tables or to information obtained from books to guide him in designing earthworks, when he has it in his own power to obtain the necessary data, either by observation of existing earthworks in the same stratum, or by experiment."

(c) *The "Historical Element" of Earthwork.*—There is a further cause of variation in the behaviour of soils, and that is what Professor Clerk Maxwell has called the "historical element," which term not only comprises the manner in which the mass was formed, but also includes the different causes at work which have subsequently modified its condition.

In respect to the effect of the original method of the formation of earthwork on its stability and behaviour, Sir G. H. Darwin[2] made experiments on "The Horizontal Thrust of a Mass of Sand," which show that when sand is formed in different ways into an embankment, it produces different amounts of thrust, although in each case the mass presents the same external appearance. This fact is recognised in engineering practice, for, when it is desired that earthwork should settle tightly against a retaining wall, its constituent layers are made to slope downwards towards the wall; the steeper the slope, the greater will be their pressure. If, however, the wall is to be freed from earth pressure, the layers are made to slope downwards away from it. The same thing occurs in Nature. "The stability of sedimentary rocks in the side of a cutting is greater when the beds are horizontal, or dip away from the cutting, than when they dip towards it."[3]

Recent experiments[4] on earth pressures showed that the amount of penetration of a weighted plunger into sand, sifted garden earth, and sifted ashes and cinders (all homogeneous materials) varied fairly regularly with the pressure; while that into clay increased enormously with the pressure, showing that for it the internal coefficient of friction falls off rapidly with increase of pressure. These experiments thus confirm the remarks made at the end of paragraph (*d*) below as to the necessity for taking special precautions in the design and construction of dams of considerable height. The angle of internal friction is not constant for any material, but varies with the degree of consolidation of its particles, and is the same as the angle of repose only when the material which is tested for penetration is in its naturally loose state, in which it is alone possible to measure its angle of repose. The angle of repose thus gives the worst condition of stability, and if adopted, as done by Rankine for determining the amount of earth pressure against a retaining wall, provides an ample factor of safety for ordinary working conditions; it of course varies with the nature of the material employed.

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[1] Rankine's "Civil Engineering," eleventh edition, p. 317.

[2] Minutes of Proceedings, Inst.C.E., Vol. LXXI.

[3] Rankine's "Civil Engineering," eleventh edition, p. 318.

[4] "Experiments on Earth Pressure," by P. M. Crosthwaite, B.A.I., M.Inst.C.E.; Minutes of Proceedings, Inst.C.E., Vol. CCIII., Paper No. 4,194.

(*d*) *The Effect on Earthwork of Causes acting subsequently to its Construction.*—Attention has not, however, always been paid to the modification of the behaviour of earthwork by the effect of causes acting on it subsequently to its construction, although it is necessary to take such effect into account. In nearly all earthworks the practice is to treat the material as homogeneous from top to base, and to adopt uniform slopes throughout. The lower portions in a high dam must, however, be in a very different condition from that of the upper ones, as they are much more highly compressed and are moister. Probably the enormous superincumbent weight causes some stratification of the lower parts and diminishes their cohesion, while the increased smoothness due to the pressure lessens their frictional resistance. The amount of increase of frictional stress, according to the depth below the surface, depends upon the viscosity of the earth enabling it to transmit pressure, and this pressure must vary from point to point on the cross-section of the dam. The increase in moisture at the base will diminish both the frictional resistance and the cohesion. The variation of the materials, and the differences in their disposition and the methods of construction, introduce further elements of change, so that there are numerous entirely hidden forces at work, of which the magnitude and resultant action can be determined only from the experience of the works themselves.

It may, however, be said that in a high earthen dam with plane slopes the resistance to slipping decreases with the increase of height from the top, and that the proper section for it is one having the slopes continuously flattened towards the base. Experience has shown that well-constructed dams up to 75 feet in height can be formed with the same slopes throughout; ones of greater height it will be advisable to construct of varying slopes, with strong toes of drystone (packed with good gritty and clayey soil to make them fairly water-tight, and to increase their resistance to slipping—Article 83 (*d*)), or with berms at the base (Art. 83 (*e*)) to buttress them.

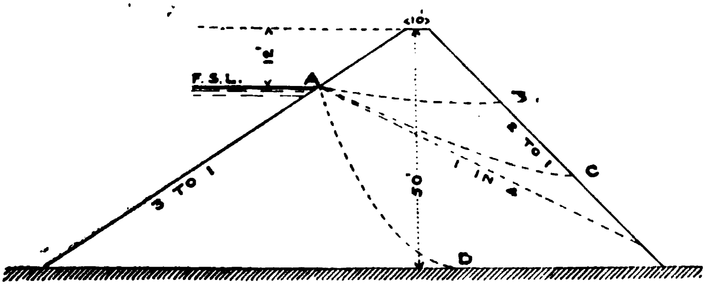
78. Percolation.

(*a*) *Through the Dam.*—Proper puddle clay is highly resistant to infiltration by water, but all ordinary earths used for dam construction are much less impervious. This fact must be recognised in the design and execution of an embankment which on the upstream face is exposed to great water pressure. Infiltration from the reservoir will decrease the weight of the submerged part of the work by that of the water displaced by it, and will thus diminish the stability of the dam in proportion to the porosity of the earthwork. Conversely, the heavier is the material of which the embankment is constructed, other things being equal, the more stable will be the structure.

The effect of the degree of porosity on resistance to infiltration is illustrated in Fig. 20, where are shown the surface lines of percolation in different cases; these lines are the hydraulic gradients of internal flow through the dam, and indicate the level to which subsoil water will rise in it. (Art. 209 (*c*)). The line AB, nearly level, represents what would occur in a bank of

FIG. 20

PERCOLATION THRO' DAM – (HOR^L TO VERT^L 1 TO 2)



dry rubble with large interstices; the stones being comparatively large and heavy, the bank would be stable until the velocity of the water between them increased sufficiently to carry them away. The line AC indicates what might happen in a badly-constructed dam, and the amount of infiltration shown would probably cause a slip. The line AD marks what exists in a properly-consolidated embankment, more especially if its downstream portion is formed of self-draining material and is underlain by base drains. The line marked "1 in 4" is that which experiments in Bombay dams have shown to be there an average slope for the percolation surface. These experiments were made by sinking iron pipes from 1½ to 2 inches in diameter with perforated ends through the embankments, and it is probable that the infiltration water was headed up in them by the pressure upstream of it; moreover, the dams were made of retentive material throughout when the importance of drainage downstream of the centre line was not realised.

The slope of the percolation line measures the resistance of the material of the dam to the flow of water through it, and the decrease in weight and stability of the dam is measured by the height at any point of the percolation line above the ground line. In addition (Art. 77 (*b*)) the saturated portion has diminished frictional and cohesive resistance to slipping. It is, therefore, of the greatest importance to construct the upstream part of the section of the dam with impervious material and to increase its resistance to infiltration by thorough consolidation.

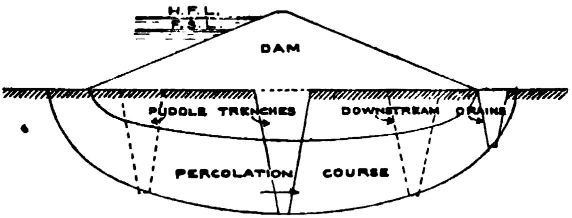
Other things being equal, the rate of percolation depends upon the subsoil hydraulic gradient; while the pressure head remains constant that gradient varies according to the distance apart of the free outlet from the inlet of subsoil flow. Therefore the more pervious the dam, the flatter should be its slopes so as to increase that distance, and thus diminish the rate of percolation (compare Art. 209 (*c*)).

If percolation to a small extent took place uniformly throughout a soundly-founded dam, and did not carry away any of its material, it would not seriously affect its stability, as is proved by many existing dams, of which few are impervious, and in cuttings through leaking strata. The danger is that the percolation water may sodden the base, or may be concentrated from a length of the dam and endeavour to find an outlet, such as a settlement crack or pervious layer; if successful in this, the flow may be able to detach from the main part of the embankment the portion of the earthwork thus separated and cause it to slip. As long as the percolation water issues clear and does not increase in amount, there is no fear that an accident will happen from it directly. Percolation can be reduced by careful selection and proper consolidation of the material used in the construction of the dam; such that still takes place should be dealt with by drainage.

(*b*) *Below the Dam.*—Theoretically the lines of flow of subsoil percolation below a dam resting on homogeneous soil and having equal side slopes are a series of confocal ellipses[1] (Fig. 21); this is owing to the effect of the weight of the dam, which increases from its toes to its centre line, and to the resistance offered by the puddle trench. They compare with the semicircular courses of subsoil flow below a simple weir built on sand (Fig. 104, p. 434). The rate of flow is greater the shorter the line of flow, and is thus at a maximum at the exit near the downstream toe. From the figure it will be seen that the central puddle trench has to be of the maximum depth, and that the trench could be reduced in depth without diminishing its efficiency by placing it more upstream; there are, however, practical objections to this (Art. 84 (*b*)). Further, it will be noticed that a drain parallel to the dam and just outside its downstream toe will tap the subsoil flow passing the puddle trench as effectually as a deeper drain formed under the dam itself. The former position is therefore best for the location of the downstream drain mentioned in Article 79 (*c*); moreover, there are practical objections to having a deep

FIG. 21

PERCOLATION BELOW DAM



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[1] Parker's "Control of Water," p. 293, George Routledge and Sons 1913.

drain under the dam, as in that position it cannot be attended to subsequently should that prove necessary.

79. Drainage.

(*a*) *General Remarks—Internal Drainage.*—Drainage is necessary to remove water which may be met with—in the heart of the dam, due to percolation from the reservoir or the wetting of the downstream slope by rain; or along the junction with the ground of the base of the dam; or through the strata underlying that base; the last two are chiefly due to leakage from the reservoir.

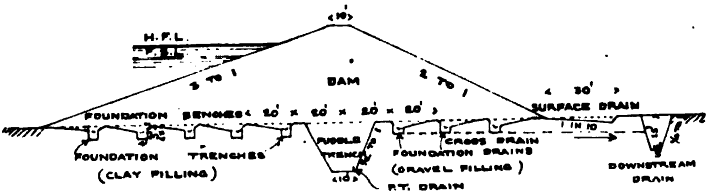
To prevent the internal percolation from entering into and remaining in excess in the embankment, its upstream portion should be constructed of clayey, water-tight material, and its downstream one of permeable material, with more grit in it to render it self-draining, and both should be well consolidated.

(*b*) *Surface Drainage.*—To deal with the leakage along the base of the dam, the surface of the natural soil should be excavated in a series of longitudinal furrows, or "foundation benches," parallel to the centre line, with the long slope next the toe of the embankment, and small "foundation trenches" should be dug along their troughs. On the upstream side the latter should be filled with water-tight material so as to make them into small puddle trenches, which will tend to resist the creep of water, to form an impermeable base for the dam, and to aid the main central puddle trench. On the downstream side the trenches should be filled with gravelly, porous material, so as to convert them into small "foundation drains," which will receive the water creeping along the surface of the foundation and that derived from the percolation through the dam, which will be led uniformly into them by the slopes of the benches. This drainage should be passed out of the dam by cross drains at intervals. To stop water from lodging downstream of the downstream toe of the embankment and soddening the ground, which might induce a slip, it is advisable to excavate a longitudinal "surface drain" parallel to and near that toe.

(*c*) *Subsoil Drainage.*—To cut off leakage through the strata underlying the dam a "puddle trench" is made, and this is usually the only precaution taken, except the clearing and roughening of the ground surface covered by the embankment. Some leakage is likely, however, not to be intercepted by it, and this will tend to soften the puddle and sodden the impermeable strata immediately downstream of the trench. To deal with this flow it is desirable to construct a longitudinal "puddle trench drain" with a continuous fall along the downstream toe of the trench, and to lead the water out of the dam by cross drains. If there are depressions in the longitudinal section of the main drain, its bed should there be supported at the proper inclination by masonry or concrete filling. Where the trench crosses the bed of the impounded stream at a low level, its drain can be drained into that bed by an upwardly-inclined cross drain, as in the case of a masonry dam (Art. 72 (*b*)). Still further to prevent the ground below and downstream of the dam from becoming sodden and incapable of resisting the weight of that heavy mass of earthwork, a "downstream drain" should be formed downstream of the surface drain, and into it should be led the discharge of the foundation, surface, and puddle trench drains ; this should be passed out of it by cross drains, where practicable, or into the river bed. These drainage arrangements are shown in Fig. 22.

FIG. 22

DRAINAGE OF BASE OF DAM


10'
H.F.L.
3 TO 1
DAM
2 TO 1
30'
SURFACE DRAIN
FOUNDATION BENCHES 20' × 20' × 20' × 20'
1 IN 10
PUDDLE TRENCH
CROSS DRAIN
FOUNDATION DRAINS (GRAVEL FILLING)
FOUNDATION TRENCHES (CLAY FILLING)
10'
P.T. DRAIN
DOWNSTREAM DRAIN

(*d*) *Drains.*—All the drains should be in discontinuous lengths, terminating at the cross drains, and separated from each other there by short lengths of undisturbed soil, so as to obviate long continuous drainage lines under or near the dam. All subsoil drains should be constructed on the principle of the reversed filter, i.e., surrounded by fine porous material to prevent them from choking ; the effect of this will probably be that in course of time the drainage will become staunched at its source by the deposit of silt. What has to be aimed at is to diminish, as far as possible, the flow of water in or under the dam upstream of its centre line, and downstream of that, to lead harmlessly away such as has not been intercepted.

At all valley lines crossed by the embankment should be "rear drains," and down the bed of the impounded stream a "main rear drain"; all these should be run at right angles to the dam with as steep a slope as possible out to the natural surface. As long as the drains run clear and their discharge does not increase in the fair weather, it shows that damage is not happening to the embankment. Should, however, the flow become discoloured, it is a sign that a leak is forming, and this should be dealt with at once by cutting out the unsound part of the dam and re-making it. A proof of the efficiency of the drainage arrangements will be afforded by the dry condition of the ground downstream; if, however, swampy places exist there, they will show that the drains are not working properly, and the defective lengths should be put right. With good drainage a well-designed and well-constructed earthen dam is rendered quite safe, as thereby the line of saturation is lowered and the foundations are secured, and thus slips are prevented. Undrained clay dams are liable to failure owing to the effects of percolation into them.

80. "Hydraulic-fill" Dams.

This type of dam is favoured in America. To form it water is pumped, or delivered from reservoirs, at high pressure through pipes ending in a nozzle so as to issue as a jet, which is directed against an elevated earth and gravel face so as to cut it down. The resulting mixture of water and earth (consisting of clay, stones, and fragments of rock) is then led by gravitation through pipes or wooden flumes on to the site of the dam, where it is deposited after "water sorting" has taken place, so that the section is built up with the rocky particles on the outside faces, and the other materials graduated to be finer and more clayey the nearer they approach the centre.

In the original practice a "summit pool" was formed on top of the dam as it was raised so as to hasten the deposit of the material and its consolidation by water pressure, and, thereafter, the water was drained off, partly through the dam itself. The result of this was, however, to induce stratification (tending subsequently to leakage), and to keep the central part of the dam as a soft, slimy clay charged with water (instead of being dense and water-tight like a puddle wall), and this led to slips. The sides of the summit pool were formed by rough banks, which rendered difficult the proper formation of the final slope. The outside of the slope was deficient in clay and fine material, so that it was highly permeable, and thus, while in a green state, admitted to the hearting water on the upstream side, which was derived from the sluicing operations and impounded by the dam. This prevented the drainage of the hearting and its consolidation (although that was thereby intended to be effected), so that slips sometimes resulted. For successful construction by this system it seems essential that—

(i) A hearting of pure retentive clay and permeable side facings should not be formed, but the whole section should be of water-tight and self-draining material;
(ii) The work should be carried up slowly and evenly to the full section, and great care should be taken to avoid stratification;
(iii) As much time as possible should be allowed for the work to drain and consolidate before it is subjected to infiltration by water from the reservoir.

In more modern practice[1] the defects mentioned above have been avoided. The water (which amounts to from eight to twenty times the volume of the dam) is not allowed to stand in a summit pool on the embankment, but is run off at once. The material is deposited as a homogeneous mass without stratification by continually changing the dumping point, is compelled to flow longitudinally with a perfectly free discharge, and is confined laterally by rough wooden shutters supported by posts set out with reference to the correct side width and raised from time to time to keep pace with the embankment (Fig. 23). Good proportions of the materials are one part by volume of clay to one of grit in the hearting and two of grit in the outside facings. In America this system is said to be quick and economical, but in the tropics, where cheap labour is available, pumping expensive, and water scarce, it is not likely it will be adopted instead of the ordinary

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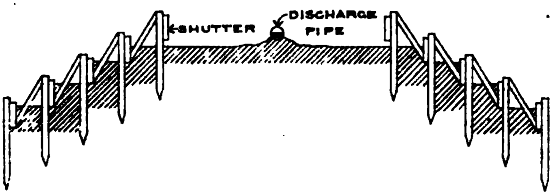
[1] "Earth Dams and their Adjuncts," The Ambursen Company, 61 Broadway, New York.

FIG. 23

FORMING SLOPES—HYDRAULIC-FILL DAM



method of conveying dry material to the site and consolidating it artificially.

81. Masonry Core Walls.

Instead of a central puddle wall American engineers prefer a masonry core wall. This should be founded on an unyielding, impervious stratum, should be thick enough to resist infiltration and pressure due to the full head of water, and rupture by unequal earth pressure, and should have its faces gently battered so that the earthwork of the dam during and after settlement may abut tightly against them. The section proposed for the new Croton Dam,[1] New York, had the trench portion 18 feet thick throughout for 89 feet from foundation level to within 36 feet of the ground surface, and was thereafter battered uniformly on both sides for 142 feet up to its top, which was 6 feet wide, and 14 feet below the top of the dam.

The following advantages are claimed for the core wall :

(i) It prevents water percolating through the upstream slope of the dam from passing into the downstrean one. (Thin masonry, is however, not absolutely water-tight under great water pressure, but may be made more staunch by cement pointing or plastering the upstream face.)

(ii) It cannot be washed out, as a puddle wall may be, should a leak through it be formed; such a leak is more likely to be silted up than enlarged.

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[1] Minutes of Proceedings, Inst.C.E., Vol. CXXXII. p. 267.

(iii) It separates the dam into two distinct portions, an upstream one, which should be made as water-tight as possible, and a downstream one, which should be formed as stable as possible. If the two portions abutted directly on each other, cracks might occur in the centre of the dam on account of differences in their settlement. (Such different settlements might, however, still happen if the core wall were built, and might lead to its fracture ; where a core wall is not designed, the nature of the earthwork would be gradually, not suddenly, varied near the centre line of the dam (Art. 87 (*b*)).

(iv) It enables the outlet culvert to be carried through the dam with perfect safety.

(v) It allows the outlet tower to be replaced by a " dry well " tower (built upstream of and in connection with the core wall), and an inlet channel from the reservoir and an outlet channel downstream, thus dispensing with the ordinary external tower and approach bridge and bank.

(vi) It gives an earthen dam greater strength to resist the erosive action of water passing over its top. (This topping of a dam should be prevented by providing sufficient waste-weir discharging power, and water should never be allowed to rise to within several feet of the top of the dam (Art. 82 (*a*)).

(vii) It can be made to form a solid support to a crest wall protecting the top of the dam from wave action. For this purpose the line of the core wall should be moved upstream to coincide with that of the upstream edge of the top of the dam. (Care will have to be taken to prevent the reservoir water getting direct access between the wall and the earthwork.)

A modified form of core wall has recently been devised. This is built hollow of reinforced concrete, with vertical cross walls at intervals, so as to make it cellular. The longitudinal walls are spaced sufficiently far apart to permit between them of inspection of the interior, and are lined externally by a dry filtering layer, which collects the drainage of the earthwork of the dam and admits it through weep holes to the centre of the core wall, from whence it is led out of the embankment by base drains on the downstream side. This design has been recommended for adoption in hydraulic-fill dams, as it is considered it will ensure the rapid drainage of the water-deposited material, and thus its early consolidation.

The core wall has several points in its favour, but its expense, which will be a considerable addition to the cost of the dam, is against its general adoption.

82. Section of the Dam.

(*a*) *Ordinary Sections.*—The proper section to be adopted for a dam depends upon—

(i) The angles of repose of the soil of which it is formed when that is saturated by the water of the reservoir or by rainfall;
(ii) The nature of its material;
(iii) The nature of the foundation;
(iv) The height to which the work has to be raised;
(v) The importance of the work.

The following table gives the general sections which may be adopted with safety and economy for all ordinary good soils properly consolidated and resting on good foundations:

1	2	3	4	5	6
Height of Top of Dam above Ground Level.	Height of Top of Dam above H.F.L.	Top Width.	Upstream Slope.	Down-stream Slope.	Width of Dam at H.F.L.
	Feet.	Feet.	Ratio of Horizontal Width to Vertical Height.		Feet.
1. 15 feet and under	4–5	6	2–1	1½–1	20–23½
2. 15 feet to 25 feet	5–6	6	2¼–1	1¾–1	27¼–31½
3. 25 feet to 50 feet	6	8	3–1	2–1	38
4. 50 feet to 75 feet	7	10	3–1	2–1	45

Above 75 feet in height special precautions have to be taken; these may consist in flattening the slopes considerably at the base, adding berms at the base, or constructing strong dry-stone toes. There are several instances of dams having been raised to 100 feet, and a few to 120 feet.

It is advisable for appearance sake to have the same section throughout the dam, as reductions at the flanks do not effect much saving unless these are very long and moderately high. In a long dam three changes at most will suffice, different sections being adopted for the gorge embankment and the high and low parts of the flank embankments. To facilitate the work of setting out, such changes should be made in lengths of 100 or 200 feet, instead of uniformly throughout the whole dam.

(*b*) *The Height of the Dam.*—The height of the dam should be reckoned from the base of the cleared foundations to the crest; and to this should be added the allowance for settlement which is usually taken from one-thirtieth to one-thirty-sixth of that height. This is a liberal amount, which is provided to ensure safety.

The "shrinkage of earthwork," i.e. the percentage diminution of its bulk when the natural soil is made into an artificial embankment, has been stated to vary generally from 8 to 12 per cent.; unfortunately, experiments on the large scale on which they can be made during the construction of works appear to be few; as they should be practicable without much difficulty, more are desirable. The final amount of shrinkage will depend upon the height of the bank and the nature of its material.

(*c*) *The "Free-Board" of the Dam.*—The "free-board" of a dam is the height of its top above high-flood level; it is required as a measure of safety in ordinary circumstances, and to provide for any accidental settlement which may occur. This height should be greater for large reservoirs than small ones, as their safety is more important, and also greater at high parts of the dam than at low ones, as the danger of excess settlement is more considerable there.

(*d*) *The Top-Width of the Dam.*—The top-width of the dam forms a footway across the work. Although some high dams carry roadways, the practice is not desirable, except for works purposes, partly because of the danger to ordinary traffic, and partly because of the damage that may be done to the work by that traffic; it is therefore better that a roadway, when necessary, should be carried on top of a berm near the base of the embankment. The top-width should be enough to provide a sufficient base for the raising of the dam should that be required to make up excess settlement, etc., and should therefore be greater for high than low works. As a decrease of top-width affects only slightly the total area of the section, it is best to maintain the top-width the same throughout the dam, and, if any reduction is contemplated, to confine it to the low ends of the flank embankment.

(*e*) *The Side Slopes of thc Dam.*—These primarily depend upon the nature of the material of the dam. As pointed out at the end of Article 77 (*d*), as dams increase in height so does their material decrease in stability, and therefore the higher the work, the greater should be its side slopes. The upstream is made flatter than the downstream one, as it usually consists of more clayey materials and is more saturated by water. At the top of the dam the side slopes can be made steeper for the sake of economy, but in the interest of safety this is not advisable, as thereby the raising of the work after undue settlement has occurred will be rendered more difficult.

(*f*) *The Sectional Area of the Dam.*—The sectional area of a dam with uniform side slopes is given by the formula—

$$A=\left\{T+H\left(\frac{S_1+S_2}{2}\right)\right\}H$$

where A is the area in square feet;
T the top width in feet;
H the total height in feet;
S_1 and S_2 the ratios of the horizontal widths of the two side slopes to their vertical height.

It will be seen from this that in high dams the top-width is a comparatively small factor, and from the table in paragraph (*a*) above that the sectional areas of different heights vary practically from one-and-three-quarters to two-and-a-half times the squares of their height.

83. Sections Required at Particular Sites.

(*a*) *Gorge Embankments.*—Where the gorge, or river crossing, is very high, it is advisable to support the base by strong drystone toes ((*d*) below). Where it is of considerable height, the dam will require a greater free-board, greater top-width, and possibly flatter side slopes than where it is of small height. To prevent any tendency to slipping from the sides of the gorge if they are steep, they should be carefully benched with base slopes inclined downwards from the natural ones, so that the earthwork during settlement may tend to move towards the flanks rather than towards the river crossing, as this might cause a slip. If one or both slopes of the gorge are precipitous, the site is unsuitable for an earthen dam, and instead a masonry one should be constructed at it.

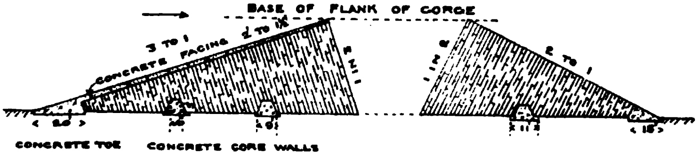
(*b*) *Inferior Foundations.*—A really bad foundation should be avoided, as no treatment short of removing all the defective material will enable the dam to be constructed safely at the site. Where the foundation consists of deep clay, which will become soft when wet, the side slopes of the dam should be flattened at the toes to secure a wider base, and steepened a little at the top to reduce the weight. The base of the downstream part of the dam and the area just below it should be carefully drained; and the former in bad cases covered with gritty casing material from about 5 feet thick at the centre to about 3 feet at the toes. On the upstream side the base should be formed with material having half the grit contained in the downstream side, so as to be nearly impermeable.

(*c*) *Sandy River Bed Foundations.*—All porous material should be removed under the upstream half of the base of the dam ; if, however, the sand is mixed with a little clay so as to be compact and solid, it may be allowed to remain under the downstream half, where it will act as a drain. If any movement of this, if unsupported, may occur through the weight of the embankment, it should be prevented by constructing a strong drystone toe wall, founded on an unyielding substratum.

(*d*) *Drystone Toes.*—If the gorge embankment has its sides confined by strong toes of some non-viscous material up to the base level of the flanks, the enclosed earthwork will be prevented from moving in any direction. After the base of

FIG. 24

DRYSTONE TOES OF DAM



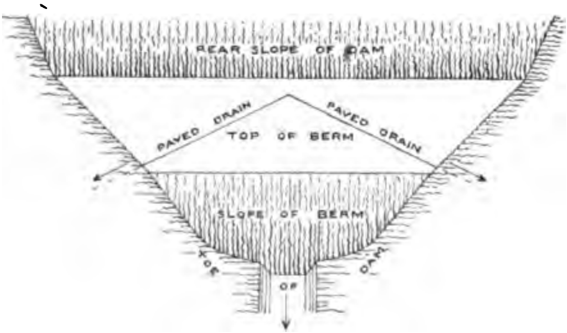
UPSTREAM TOE DOWNSTREAM TOE

such a gorge dam has been allowed to attain practically final consolidation by settlement, the upper part can safely be raised on this reliable foundation to the ordinary section of the flank embankment (Fig. 24).

To give greater frictional resistance to slipping, and to prevent the infiltration of water on the upstream side, rubble masonry, or concrete, toe and core walls should be built into the foundation, so as to project into and key with the superstructure; on the downstream side the toes and core walls should be pierced at intervals by slab drains to pass off the intercepted drainage. The water face of the upstream toe should be laid in masonry, or covered with concrete, to prevent water from entering and buoying it up. The body of the toes should be formed of rough rubble laid in layers roughly normal to the outer slopes; the stones should break joint with each other, and interlock with those of the layer above them. To increase the impermeability and resistance to slipping of the stones they should be bedded firmly in gritty clay, and their joints should be packed with it by working it into them by short iron bars; each large interstice should be filled by a single spaul of the largest size practicable driven into it. This type of dam with drystone toes is the one best adapted for embankments exceeding 75 feet in height, and with them works may safely be constructed up to 125 feet in height.

FIG. 25

PLAN OF BERM



(*e*) *Berms.*—A berm is a buttress to a dam at its toe which is the weakest part of the section. The frictional resistance to slipping of an embankment is a measure of its weight, and is independent of the area of its base, but its cohesive resistance is a measure of that area. A berm is thus effective in that it increases the area of the base more than the material in it would do were it distributed evenly or in a series of small berms all down the slope. The chief advantages of a berm are that by its great increase of the section of the dam it tends to prevent any dislocation at the top from extending to the base, and any bulging of the subsoil at the toe. Further, it virtually reduces the height of the dam where that is suddenly increased, as at the river crossing. Finally, in the case of a badly-constructed dam with a flat percolation line (Art. 78) the addition of a berm will weight and buttress the embankment by forming a toe of dry stable material to the unduly saturated base. A berm is also useful for carrying a road across a gorge, or at the foot of the dam, and for passing off from the slopes the large amount of drainage due to heavy rainfall (Fig. 25).

(*f*) *Toe Walls.*—A toe wall is another device to prevent motion at the toe. Fig. 26 shows a form which is designed to secure the foundation of the dam, and not its superstructure. A trench is excavated through the unreliable foundation and is filled with drystone, which is weighted by the superstructure of the wall, and thus kept in place.

SECTIONS OF TOE WALLS

FIG. 26

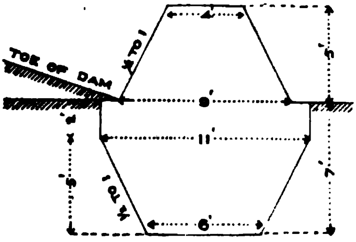


FIG. 27

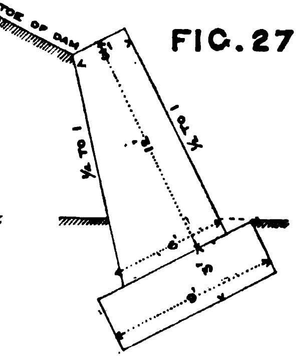


Fig. 27 shows a form (really a retaining wall) which is intended to support the toe of the dam in the same way as does a berm. By reason of the double batter of its section towards the embankment, it offers an active resistance to the motion of the earthwork, and not merely the passive one of its stable weight.

On the upstream side of the wall a drystone lining should be laid, and the drainage thereby collected should be passed out of the wall by small slab drains or large weep holes at the base.

(*g*) *Breaching Sections.*—While it is desirable to raise the more important parts of the dam higher than the less important ones, it is also advisable in a large work that even the latter should not be topped in abnormal circumstances. To guard against this a " breaching section " should be formed when safely and economically practicable. Its top should be about 2 feet lower than that of the flank embankment, its top-width reduced to about 6 feet, and its side slopes steepened as much as is quite safe in ordinary conditions. It can thus be speedily cut down when danger threatens, or, at the worst, will breach automatically during an abnormally high flood.

It should be located where there is a natural saddle in the ridge line, but where this does not exist an artificial one should be formed by excavation. The best outfall is towards the waste weir channel, as then the flood discharge from it will do the least damage. To be effective the breaching section should be long if the embankment at it is low; if that is high, its length may naturally be shorter. Too great a height of dam is, however, a disadvantageous location, for, when such a low-level breaching section came into operation, it would tend to produce a deep scour channel, and thus to lower the reservoir greatly and to increase the cost of reconstruction unduly. As a general rule, it may be said that the breaching section should be situated where fairly hard material is not more than 4 feet below full-supply level.

84. The Puddle Trench.

(*a*) *Object of the Trench.*—Practically no subsoils are water-tight, especially under the great pressure of water in a reservoir. Ordinary subsoils may be porous, when water will pass through them as seepage, or they may have open or dry planes between the layers through which it will percolate as leakage. The object of a puddle trench is to interpose a *septum*, as nearly water-tight as possible, to prevent the passage through it of water coming to it; it thus tends to keep all the material downstream of it as dry as practicable.

(*b*) *Position of the Trench.*—Theoretically, assuming that the dam itself is impermeable, and the ground underlying it is homogeneous, owing to the varying superincumbent pressure at different points due to the section of the embankment, the lines of subsoil flow are a series of confocal ellipses (Fig. 21, p. 165), of which the vertical axis is in the centre line of the dam. Thus a comparatively shallow trench near the upstream toe will cut off as much of that flow as a deeper one at the centre line, and the former will preserve dry more of the base of the embankment. However, a dam is permeable, and a trench near the toe will be passed over by infiltration through the superstructure; moreover, puddle being highly compressible, in this position it will lead to unequal and non-symmetrical settlement of the embankment near the reservoir; lastly, if there is a central puddle wall, a puddle trench at the toe will not be in vertical connection with it. For these reasons a puddle trench is usually made on the centre line of the dam; there it will receive the greatest amount of compression by the superstructure, which will increase its density and therefore its water-tightness, the embankment will settle symmetrically over it, and the puddle wall will be in vertical continuation of it.

(*c*) *Depth of the Trench.*—The water filtering towards the puddle trench, and not being able to pass quickly through it, will endeavour to get under it, but a depth will eventually be reached when the frictional resistance to flow of the subsoil will be greater than that due to the transverse passage of the puddle; when this occurs the trench need not be deepened, as the rate of the filtration possible through it will then be more than that actually coming to it. The determination of this depth is a matter of judgment; it is essential that the trench should intercept such underground flow as would carry away particles of the subsoil and eventually undermine and destroy the dam; it is less important that it should be deepened so as to cut off only a small amount of harmless leakage. Assuming that good compact soils are met with, the puddle trench need not ordinarily exceed one-half the depth of the full-supply storage above its top, and that the soils are fairly compact, not more than the depth of that storage. The minimum depth at the flanks where sound rock is not met with should be 6 feet. The trench should extend from the high-flood margin on one bank to that on the other bank, or as far as may be necessary to cut off any subsoil percolation which might otherwise outflank the dam. Dams with shallow puddle trenches have stood successfully, more especially if these have been drained (Art. 79 (*c*)), a precaution which it is generally advisable to take, and one that will be cheaper than a considerable deepening of the trench. Trial pits extending for some depth should always be sunk in the bed prepared for the trench, when that is in soil, so that the nature of the substrata in regard to permeability may be tested; in particular, such pits should be excavated where the main and minor drainages cross the line of the dam.

(*d*) *Bottom-Width of the Trench.*—The bottom-width of the puddle trench depends upon—

- (i) The nature of the strata passed through, and especially of those near its foundation level;
- (ii) The nature of the filling and the amount of consolidation to be given to it, particularly at the base of the trench;
- (iii) The depth of the full-supply storage at the point considered and the importance and size of the reservoir.

That width is a factor governing the general thickness of the trench, which must be regulated in accordance with the amount of infiltering water that has to be intercepted. In important dams it is desirable that the filling should be consolidated by rolling, for which a minimum of 10 feet is required for the bottom-width; for less important ones, where the filling is compacted by ramming, the width may be reduced to 6 feet. In English practice it is usual to make the width of the trench at ground level equal to the height of the embankment above it.

(*e*) *Side Slopes of the Trench.*—The direct rate of infiltration in a homogeneous soil decreases from the top to the bottom of a puddle trench, and therefore the best section for that work is a truncated wedge, such as an open excavation with side slopes would form. Those slopes should be flat enough—

- (i) To stand during excavation and until the filling has been completed—as the time involved is short, the slopes may be steeper than those necessary for permanent stability.
- (ii) To give the filling a width increasing sufficiently as it rises towards ground level to resist the greater infiltration which will be met at the higher levels.

(*f*) *Continuity of the Trench.*—If the puddle filling is disturbed so that it becomes fractured, a leak may result, and this may increase to a dangerous extent owing to the soluble character of the material. Such a fracture is likely to occur at any sudden change in the section of the trench on account of the compressibility of the filling; for this reason there must not be cross steps at the bed, nor projecting shoulders on the sides. The trench, both in longitudinal and cross-section, must be bounded by slopes, and thus be wedge-shaped, so that the only results of the settlement of the puddle will be to make it more compact and fill the excavation more completely.

(*g*) *Filling the Trench.*—The filling should consist of the most retentive clay readily procurable, and gritty material should not be mixed with it, as this will render the mass more permeable, and is not required to increase its stability since it is confined on all sides. The excellent clay puddle which is used in England is rarely found in India, and therefore the section of the trench and the method of its filling, as here described, have there to be adapted to the inferior material which is all that is generally available. The filling must be constructed as a compact mass completely occupying the whole section of the trench, and be quite free from all leakage planes, due either to cracking or to badly consolidated or otherwise porous layers. To ensure compactness only slightly damp material should be used, and this should be thoroughly consolidated, preferably by rollers. To prevent cracking, the different layers should be constructed as rapidly as possible one on top of the other, and if work is delayed from any cause, the surface attained should be kept moist until the filling can be completed, or, if cracked, should then be dug out and re-made.

In England, after the clay is dug, puddle is prepared by cross-cutting, watering, and working it in layers, which are then trodden and kneaded into a homogeneous mass. This preparation can be carried out on the embankment itself, but a better arrangement is to make the puddle at the site of the excavation and carry it on to the dam, so that the clay may be turned over more frequently and its supersaturation may be avoided.

(*h*) *Concrete Trenches.*—These are seldom constructed in India on account of their expense, but are often made in England, especially when the depth of the trench is great. The thickness of a concrete trench depends partly upon the width necessary for its timbering, and partly upon the porosity of the strata passed through. To prevent the formation of leakage planes, the concrete should consist of fine aggregate and be rich in mortar; it should be deposited in place and not thrown down from a height; it should be thoroughly rammed to fill the trench completely; it should be constructed rapidly in thin layers one on top of the other for at least 2 feet in thickness; and the surface of the old layer should be roughened and then coated with mortar before the new one is formed on it. The trench can be drained by making on its downstream side a casing of dry material with outfall cross drains at intervals.

85. The Puddle Wall.

(*a*) *Central Puddle Walls.*—In England it is the general practice to make a puddle wall along the centre line of the dam and vertically over the puddle trench, so as to form with it a water-tight *septum* (extending throughout the embankment from below bed-rock level to above high-flood level) in order to intercept any infiltration that may have penetrated so far. In this position the quantity of the wall is reduced to the minimum, and the puddle is most effectually protected from the action of the reservoir and the weather, and from perforation by vermin. It may, however, be distorted or broken by the settlement of itself, or by the unequal settlement of the embankment on each side; it cannot be inspected or repaired to any depth, and it tends to keep the dam upstream of it saturated with water.

Rankine[1] states that the thickness of the base of a puddle wall should be one-third of its height, and that the top should be two-thirds, or one-half, of its base. In certain dams the top width varies from 4 to 10 feet, and the side batters from 1 in 8 to 1 in 16; in others the top width is 10 feet, and the side batters 1 inch per foot; a base width of one-fifth the maximum pressure head has been given in one example.

In order to avoid too sudden a change of material, which may lead to unequal and considerable settlement, the puddle wall in England is supported on each side by "selected material," which, although less clayey and less worked than the puddle, is in both these respects superior to the ordinary earthwork of the embankment. Thus the difference of settlement between the puddle and the earthwork is made less abrupt; however, it takes place at two planes instead of at one on each side of the centre line of the dam. The selected material may have on each side of the puddle wall a top-width of from 5 to 10 feet, and side slope of 1 to 1, and is carried up practically to the top of the dam.

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[1] Rankine's "Civil Engineering," eleventh edition, p. 704.

(*b*) *Slope Puddle Walls.*—Another position in which the puddle wall has been placed is on the upstream slope of the dam, so as to form a waterproof covering to it. Here it has the advantages that it will settle regularly with the embankment, can easily be inspected and repaired, and prevents excess infiltration into the whole mass of the work. It has, however, the disadvantages that it is not in direct connection with the puddle trench, its volume, and thus its cost, are at a maximum, it is exposed directly to the reservoir water, the weather, and to burrowing rats and crabs, and it may not be able to stand at the ordinary slope of the dam. The puddle wall has been constructed in a position intermediate between the upstream slope and the centre line of the dam, and there has advantages and disadvantages between those described above.

(*c*) *General Remarks.*—In India puddle walls are not now made on account of their disadvantages. It is there preferred to form the dam as one homogeneous whole, and recognised that the introduction of the puddle wall destroys that homogeneity. It would appear that in adopting the puddle wall English engineers are influenced by the excellence of the clay at their disposal, and rely upon it to make good the permeability of the general mass of the dam due to its want of artificial consolidation or to the inferiority of its material.

Compared with a masonry core, a puddle wall of the same cost has the advantages of greater water-tightness and of flexibility, whereby it can better conform to changes due to the unequal settlement of the earthwork on each side of it. Compared with each other, the central type of puddle wall appears to be better than the slope form.

86. The Foundations of the Dam.

(*a*) *Order of Suitability.*—An earthen dam requires for its foundation a base which is strong enough, even when moistened by infiltration from the reservoir, to carry it without sensible compression, or if compressible, to be only slightly and uniformly so; is of sound, compact, and impermeable material, free from porous layers and leakage joints; and is firmly united to the substrata so that it will not slip. If these conditions are fulfilled, it is not necessary to obtain for an earthen dam the absolutely rigid foundation which is essential for a masonry dam, and thus sites can be utilised for the former which would either be impracticable or economically impossible for the latter.

The best foundation for an earthen dam is one of solid, unfissured rock, and the next best one of less compact rock, the unsound parts of which upstream of the puddle would have to be removed, but those which are downstream, if securely attached to the underlying rock, might be allowed to remain for drainage purposes. Rock foundations are best when practically level, or sloping slightly downwards upstream, but those with a gentle slope downwards downstream may be roughened sufficiently by shallow longitudinal trenches excavated in them, and low longitudinal core walls built on them, so as to prevent the slipping of the dam and to unite it water-tightly with the rock.

In regard to soils, the more compact and water-tight they are the better. It is advisable to drain the foundations in them, and when the material will soften when wet, it is absolutely necessary to do this. Some engineers prefer a clay seating to a rock one, as they consider with it the dam will be in more water-tight connection with its base, but sufficient union can be obtained with rock, as noted above. All soils which are suitable for the formation of the dam are also good for its foundation; those which are unsuitable for making the embankment (Art. 87 (*a*)) are bad for its foundation, and must be removed; if on account of their depth this is economically impracticable, the site must be rejected.

(*b*) *Preparation of the Foundations.*—The maximum amounts of leakage from the reservoir and percolation from the interior of the dam tend to find their way along the base of the embankment. The natural surface of the ground, owing to the absence of pressure on it and to the influence of the weather on it, is generally not compact enough to be water-tight, and unless precautions are taken, the base of the dam may become soddened by percolation. The way the foundations should be cleared and drained is described in Article 79.

The foundation should not only be thoroughly drained, but should be prepared so as to secure the stability of the dam and prevent any tendency to slipping. The proposed system of foundation benches is useful not only for drainage, but also for obtaining that stability, as a dam resting on their sloping surfaces will tend to settle towards its centre line and compress itself, and not away from that and slip. For low and unimportant dams it will suffice to clear off loose surface soil, and harrow, or roughen, the exposed surface, so that the dam may unite with the underlying compact soil. Similarly, the surface of the foundation benches should be roughened. At the toes of the dam the weight of the superstructure is much less than what it is near the centre line; the depth of the foundation work may therefore be made less for the former than is necessary for the latter.

87. The Materials for Dam Construction.

(*a*) *Selection of Material.*—The material for a dam requires careful selection, as it must be both water-tight and non-slipping. Soils which are highly compressible like peat, those which are powdery and will not bind, those which are charged with salts, or when wet become slushy, and those which when dry break into fragments with sharp angles and smooth, shining surfaces, should be rejected. The most suitable material is one containing enough clayey matter to enable it to bind and thus become water-tight, and enough shaly matter to give it frictional resistance to slipping, and the property of self-drainage, so that the whole mass never becomes sodden. The best natural soils break into tough, not brittle, fragments, and have a dull and irregular fracture. When the suitability of a soil is doubtful, small trial tanks should be made with it and filled with water; the behaviour of their banks should be noted when they are saturated, and after they have been allowed to dry. If the surface of the banks cracks during desiccation, more shaly matter should be mixed with the soil. The best kind of soil consists of one part of clayey to one part of shaly material; if it is not naturally procurable, it should be made with these proportions by artificial mixture of the available soils.

Pure sand has, however, been used for some dams, as it has the property of settling into a compact and not highly permeable mass when wetted, while the angular form of the particles gives it a considerable amount of resistance to slipping. Sand in combination with clay is bad, as it admits water, but the clay does not allow this to drain out; the fineness of the grains of sand prevents it from giving much frictional stability to the clay, which by itself is slippery. Pure clays and rich clayey earths absorb and retain much water, and thus become greasy and liable to slip.

The material required for the dam must not be obtained from its immediate neighbourhood, as the excavation there might weaken the base of the embankment and induce percolation through permeable soils, if these are thereby uncovered. For these reasons the ground should not be excavated within four times the height of the dam on the upstream, and twice that height on the downstream side, measured from its toes; nor should pervious soils in the reservoir bed be exposed within ten times that height.

(*b*) *The Disposition of Material in the Dam.*—The different dispositions of material were briefly noted in Article 76 (i) to (iii); that described in the last will now be dealt with more fully. When dams were made wholly of black "cotton soil," the object in view was to secure water-tightness, and the danger of slipping resulting from its use was then not realised. With the kind of soil recommended, one part of clay to one part of shaly material, the tendency to slipping is avoided, and water-tightness is secured by thorough consolidation. The great advantage of having a homogeneous section is that it will act uniformly as one mass during the process of settlement and self-consolidation; thus will be obviated the formation of internal stresses, owing to the different rates of settlement which would occur were the section made of different materials. An earthen dam differs from a masonry one in the large amount of settlement which may take place in it; the work should therefore be constructed of material which will allow self-consolidation to proceed uniformly and thus safely. A difference of settlement might result in a slip, and might, anyhow, affect the disposition of the material of the dam and lead to cracks, leakage planes, and irregularities. Moreover, there is the practical advantage attending the use of a uniform material that thereby construction is made easier.

If, however, on account of the scarcity of one kind of soil and the abundance of another, it would not be economical to use the same mixture throughout, the upstream part of the dam should be made richer in clayey, and the downstream part in shaly, material, the change in constitution being gradually varied throughout the section. The former will thus gain in water-tightness and the latter in stability at the expense of the greater tendency to unequal settlement and greater difficulty in securing correct proportions throughout the mass. Thus all sound spoil can be utilised in constructing the dam, even rocky *débris* can be disposed of at the toe of the downstream slope where it will add stability by its weight.

(*c*) *The Casings of the Dam.*—Owing to their narrow width the casings do not sensibly affect the settlement of the dam; their object is to protect the interior from external influences. The upstream one forms a firm and insoluble foundation for the pitching, and the downstream one a covering which will not be cracked by the sun nor guttered by the rainfall. As the intensity of these external influences becomes greater from the top to the base of the dam, so should the width of the casings be increased. The actual top of the dam and the side slopes to high-flood level might have a casing 2 feet thick, and thereafter its normal thickness might be widened uniformly at the rate of 1 foot to 10 feet vertical. The casings should consist of one part of clayey to two parts of shaly material.

88. The Construction of the Embankment.

(*a*) *General Formation.*—The method of constructing the dam is: first to wet slightly the layer last completed; on the moistened surface to spread and mix the material of the new layer; and then to consolidate it. On the completion of a layer the process is to be repeated similarly for the next one, and so on.

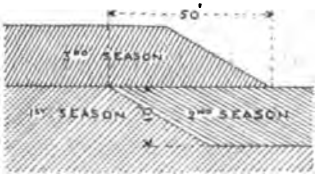
(*b*) *Watering.*—When clay is wetted it expands, and thus becomes more porous, it also becomes softer and more inclined to slip; moreover, when once wetted, it takes a long time to dry. It is therefore necessary in the interest of the water-tightness and stability of the dam to limit the water used during construction to the amount just sufficient to unite the new layer with the old one, so as to produce a solid mass free from stratification, which is the sole object of watering the earthwork.

(*c*) *Spreading and Mixing.*—The purpose of spreading and mixing the soils of which the dam is formed is to obtain a uniform material evenly disposed and thoroughly incorporated, by hand or by harrows, so as to avoid stratification. Were mixing not done, the clay might form slipping planes, and the shale leakage planes, and both of these might endanger the safety of the work. The layers should have small thickness, so that they may be properly consolidated, and should be formed with slopes to the centre of the dam to give the earthwork a tendency to slip inwards rather than outwards. The thickness of the layers completed by ordinary rolling should not exceed 5 inches for the top 30 feet in height of the dam, 4 inches for the next 30 feet, and 3 inches for the remainder of the base of the dam and for the river crossing. When steam rollers are used these thicknesses may be increased by 50 per cent.

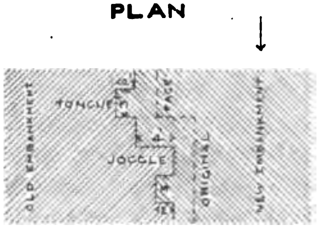
In England the material is often tipped from wagons, and as the individual tips have not a wide face, there are between them many troughs filled with less consolidated material. To render the construction more homogeneous it is advisable to keep the tipped layers down to a maximum of 30 inches in thickness, and to consolidate them well by rolling. With layers of even such reduced thickness uniform and complete consolidation does not, however, appear practicable.

FIG. 28

CROSS-SECTIONAL JUNCTION



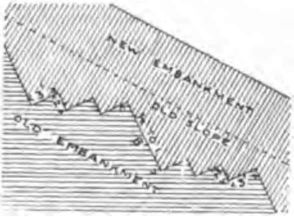
PLAN



(*d*) *Consolidation.*—In order to render the earthwork thoroughly and uniformly dense, it should be consolidated artificially as much as possible and evenly throughout the section. Thus the final consolidation due to settlement will be less in amount, and during it the earthwork will remain regular, the layers will be maintained unchanged, and the formation of leakage and slipping planes will be prevented. An originally loose structure will at first be subject to great infiltration from rain and from the reservoir, which will keep it green for a long time; this will tend to cause great and unequal settlement (due to the variation in the heights of the cross-section) and to offer less resistance to further infiltration during the process of self-consolidation of the dam. Artificial consolidation during construction is therefore of the utmost importance, and the more thoroughly it can be done the better; it is the chief means whereby is resisted percolation, the principal danger to earthen dams. As a further precaution in the same direction the dam should be allowed to self-consolidate in the dry for as long as possible before it is subjected to infiltration from the reservoir.

FIG. 29

LONGITUDINAL JUNCTION

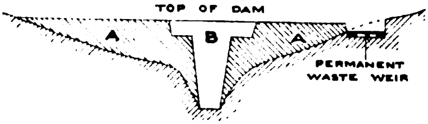


(*e*) *Junctions of Earthwork.*—Junctions of new to old earthwork should be avoided as much as possible, as the rates of settlement of the two will differ until practically final consolidation is attained, and until then there is a risk of separation taking place between them. When such junctions are unavoidable, cross-sectional ones should be made as illustrated in Fig. 28, and longitudinal ones as in Fig. 29; the former have to resist the tendency to the formation of leaks, and the latter of slips.

89. The Closure of the Dam.

FIG. 30

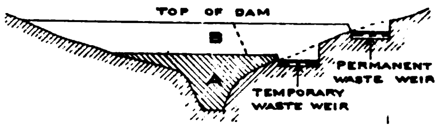
USUAL CLOSURE



(*a*) *Alternative Methods.*—On account of the largeness of floods in the tropics it is not practicable to divert them outside the dam during its construction by bye-wash channels, and they have therefore to be passed through it then in a gap left for the purpose. The closure of a high dam there is thus a difficult work, as it ought, if possible, to be effected in a single season and well before the commencement of the monsoon. Originally it was effected as shown in Fig. 30, but there are many objections to this, and the closure should preferably be carried out as sketched in Fig. 31. In this latter arrangement the dam is raised in continuous level stages, commencing with the one at its lowest base at A, and working gradually up to that forming its final crest, B. To provide for the passage of floodwater, a temporary waste weir is made at a suitable site in the longitudinal section, so that it can discharge the maximum flood with safety. The advantages thus secured are:

FIG. 31

PROPER CLOSURE



(i) The junction between A and B is of minimum height, and therefore the difference of settlement at it will be very small.

(ii) A is at first subjected to infiltration only from a shallow reservoir, which cannot penetrate it far and keep it green. All the upper part of the dam, except the low closure of the temporary waste weir, can be allowed to consolidate before water comes against it.

(iii) The bulk of the dam, and particularly its highest sections, can be carried up slowly and evenly, so as to self-consolidate regularly. Only the low closure of the temporary waste weir will have to be done in one season.

(iv) The work can be executed without fear of delay by strikes, as the final closure of B involves the construction of a comparatively small quantity of embankment, especially if the flank (to the left of the dotted line) is completed beforehand.

(v) The construction of A will lead to the formation of a small reservoir, which will be useful for works purposes, and save water charges.

(vi) The temporary waste weir will often provide a level site for the location of the outlet, away from the gorge embankment, and below the general bed of the dam.

It will be seen from Fig. 30 that the other form of closure does not secure any of these advantages, and involves the danger of a junction at the highest part of the dam between the settled earthwork of A and the green earthwork of B, which may cause a leak to form owing to subsequent unequal settlement; this form can, however, be adopted without much risk for a low dam.

(*b*) *The Temporary Waste Weir.*—The best natural site for this weir is at a depressed saddle in the line of the dam, as then the floods passing down it will be confined in a natural channel; failing such a site, an artificial channel should be excavated, so that the tail-flood surface may be below ground level. The bed of the channel should preferably be of rock, but this need not be of the hardest character, as the work will be in operation only for a short time. If the bed is soft, and therefore liable to erosion, it should be protected near the dam by one or more masonry curtain walls. As the dam will be in an unfinished state, the discharging capacity of the temporary waste weir should be a little greater than that of the permanent one.

90. The Repair of Slips.

(*a*) *General Remarks.*—A slip of a dam is usually the result of excessive percolation into it, which either soddens and softens its base so that it cannot support the embankment, or penetrates fissures and leakage planes whereby a portion of the earthwork is detached from the main mass. Every precaution should therefore be taken during the formation of the dam to prevent a slip by proper preparation of the foundations, careful selection, mixture, and consolidation of the materials, uniform and slow construction, and thorough drainage. Even greater care is required in repairing a slip, and particularly in thoroughly draining it.

(*b*) *Slips in Pure Clayey Soils.*—A slip in such a soil has a smooth, unctuous surface, and parallel planes of similar surface are formed for some feet on each side of it. It is doubtful if these will ever disappear of themselves; the result is that the fallen mass rests on a series of steeply-tilted, smooth, lubricated planes, and is itself traversed by minor slipping planes and by fissures which will admit rainwater and reduce the frictional and cohesive resistance to motion. No dependence can therefore be placed upon it, and the only sound system of repair consists in entirely removing it and in replacing it by trustworthy material.

(*c*) *Slips in Gritty Soils.*—Where a slip occurs in earthwork having proper proportions of clay and grit, the latter will enable the whole to re-unite gradually by self-drainage and settlement, but the junction will always be a plane of weakness. To aid that self-drainage the first repair operation is to drain the slipped earthwork by drains along the junctions with the stable part of the dam, and by intermediate ones at right angles to its centre line. The excavation should be taken out in timbered trenches, and the refilling should consist of highly gritty, self-draining clay, with base drains leading out of the dam. The next step is to construct a strong well-drained drystone wall, parallel to the axis of the dam, extending throughout the slip into the stable flanks, and with good batters against the slip (Fig. 27, p. 177), so as to increase the stability of the new earthwork. If the fallen earthwork at the toe is to be removed entirely, this wall may be placed about the centre of the width of the slip ; if that is to be allowed to remain, the wall should be built at its toe. To add to the stability of the repair, a strong and well-drained earthen berm, should be formed just beyond the original toe of the dam, and its own toe should be secured by a second drystone wall (Fig. 26, p. 177). All these drains and walls should, if possible, be founded on rock, but where this is not met at a reasonable depth, they should be carried well into the natural subsoil and beyond the limit of disturbance caused by the slip. All open excavations should be taken out in sections with sufficient widths of undisturbed material between them to act as buttresses, and should be filled as quickly as possible.

91. Pitching.

(*a*) *Object and Kinds of Pitching.*—In a large reservoir the action of the wind on the water surface will cause the formation of waves, which, if allowed to break on the unprotected surface of the dam, will very soon wash away the earthwork. Hence the upstream slope requires protection by a covering which is hard, durable, and not liable to be displaced by the waves or by the growth of shrubs. The principal kinds of ordinary protective coverings are :

(i) Drystone pitching.
(ii) Concrete-packed pitching.
(iii) Concrete pitching.
(iv) Brick pitching.
(v) Bitumen sheeting.

All forms of pitching are best laid after the dam has attained its practically final consolidation, so that further small settlement will not much affect the covering.

(*b*) *Extent of Pitching.*—Stevenson's formula for the height of waves, H, is:

$$H=\tfrac{1}{3}\{1{\cdot}5\sqrt{F}+(2{\cdot}5-\sqrt[4]{F})\}$$

where F is the "fetch" (or distance for which it acts on the water) of the wind in miles. The depth of the pitching should be about one-third of H, subject to a minimum of 6 inches in small and of 9 inches in large reservoirs. It will thus increase from the bottom to the top of the dam as the water spread of the reservoir gets larger.

The above formula gives the total height of the wave from its trough to its crest. Assuming that half of this is above and half below still-water level, the top of the pitching should be raised $\frac{H}{2}$ on this account. In addition, must be an allowance for the height to which the water will be carried after the wave has broken, and that depends upon the nature of the surface of the slope of the dam, the alignment of the dam with respect to the direction of the wind, and the force of the wind at the dam. The waves will reach the dam, no matter what is its inclination to their course, at the height due to the fetch, but the effect of the wind on their crests will be influenced by the sine of the angle the dam makes with its direction, which alters the length of the travel of the wave up the pitching. Thus, when the dam is parallel to the wind, sine 0° = 0 and the vertical travel will be *nil.* When it is at right angles, sine 90° = 1 and that travel will be at its maximum. In regard to the angle which the wind makes with the dam, it must be remembered that, unless this is constant when the reservoir is full, no reduction on this account can safely be made.

Rough pitching offers the maximum surface resistance to the travel of wave-splash; where it is laid it should extend above high-flood level for at least a vertical height equal to H, and should be finished off with a wave-breaker course projecting, say, 9 inches beyond the surface of the pitching. The most complete protection to the dam will be afforded by constructing its entire free-board as a drystone crest wall with a batter on the reservoir side of, say, ½ to 1, as this will make the waves return on themselves.

(*c*) *Drystone Pitching.*—This is the kind adopted generally in India. It consists of a single layer of stones laid on a 6-inch layer of quarry spauls, the object of which is to prevent the entry of burrowing vermin, the growth of plants, and the sapping action of water finding its way through the interstices of the stones, which would otherwise wash out the underlying earthwork and undermine and destroy the continuity of the pitching. The stones should be hammer-dressed, and should be malleted securely against each other and on to their seats. After the laying has been passed, all large interstices should be filled, each with a single large chip well driven home, so as to wedge the stones firmly to each other. The defects to be avoided in pitching are: Unsound material; larger base of stone laid uppermost; long, unbroken joints; stones set with the longest dimensions of their bases not roughly parallel to the centre line of the dam; sharp abutting edges involving large interstices; stones projecting irregularly; loosely placed stones; partial bedding of bases of stones; bad fitting of bases of stones; loose packing and incomplete filling of interstices.

(*d*) *Concrete-packed Pitching.*—Drystone pitching is the cheapest reliable form of protection. It has not, however, a very sightly appearance, cannot be examined quickly, and has interstices between which waves may act and vermin penetrate. To remedy these defects the interstices might be completely filled with fine concrete, or coarse mortar, so as to unite the stones into a continuous covering.

(*e*) *Concrete Pitching.*—This may be formed of slabs of convenient size for handling, laid dry with thin joints, or the coating may be made on the slope of the dam in sections, say, 10 feet long horizontally and 5 feet wide, separated from each other by fine joints to enable the whole to follow the dam during its settlement. Although the concrete covers the surface more thoroughly than pitching stones do, it is not so durable as they are, and is apt to wear at the joints under wave action. It should be laid on a layer of quarry spauls to prevent its being undermined by wave-sapping, which may lead to its slipping off the dam. To obviate this and tie the coating on to the water slope it is advisable to embed in that at intervals header stones passing through the concrete and into the earthwork. An objection to smooth-surfaced coverings is that waves are likely to travel up them unimpeded for some distance. To prevent this there should be a wave-breaker course at the top.

(*f*) *Brick Pitching.*—This form has been laid on some river embankments in Sind, and might be constructed on small reservoirs where stone is not available, being laid stretcher-wise for small and header-wise for moderate-sized reservoirs. Bricks are scarcely hard enough to resist the impact of large waves, and cannot be made of sufficient depth to withstand it. Like stones, they should be laid in a single layer, for were two or more layers built, the water would get in between them and tend to cause the upper layer to slide on or lift from the lower one.

(*g*) *Bitumen Sheeting.*—This has been used in temperate climates for small waterworks reservoirs to secure water-tightness. If used in the tropics it would have to be protected from the heat of the sun, and if laid under earth for this purpose, would require protection from wave wash. It is thus not adapted for use on large reservoirs, and will generally be too expensive for small ones.

92. The Waste Weir.

(*a*) *General Remarks.*—The object of the waste weir is to provide a passage for the discharge of floods so that the water in the reservoir may never rise higher than a safe height below the top of the dam (Art. 82 (*a*) and (*c*)). The site available for the waste weir usually determines whether the storage work is possible or not. The essentials required for it are sufficient length, a flat longitudinal and a gently sloping cross-section, hard strata, the proper elevation, and a good outfall. The length is necessary to get discharging capacity ; the flat sections and hard strata, to diminish the cost of the works, and to obtain security for them ; the elevation of the weir crest depends upon considerations of storage ; and the good outfall is wanted so as to lessen damage by floods. The best site is generally on a long, somewhat narrow level ridge of hard material, with a gentle slope downstream.

(*b*) *Discharging Capacity.*—It is essential that the waste weir should be able to discharge safely the maximum flood possible (Art. 52), and as it constitutes the safety valve of the reservoir, that discharge must not be underestimated.

(i) Where flood observations have been recorded for twenty-five years an allowance of 10 per cent. over the highest-known flood should be made to provide for an abnormal flood, unless such a flood occurred in the period observed. Where the record is shorter, the allowance should be greater.

(ii) When a reservoir is downstream of another one, which may breach, or is liable to be visited by a cyclone, extra flood provision should be made for the abnormal discharge which may thus reach the work. That provision may consist in lengthening the waste weir, or in forming high-level safety flood cuts (para. (*f*)) or breaching sections (Art. 83 (*g*)) in addition.

(iii) The discharging power of a waste weir depends upon the unobstructed normal width of its approach channel (Art. 30), and of the portion of its tail channel just downstream of its crest.

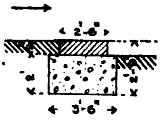
(*c*) *Usual Forms of Waste Weir.*—The usual forms of waste weirs are noted on below:

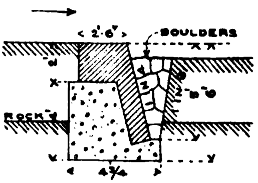
(i) Drowned Channel. This is an excavation having the crest of the weir at its bed level, and the tail channel falling therefrom. Where there is fear of the natural crest being scoured, a waste weir wall should be built at it, with its top at crest level, so as to preserve the full-supply level of the reservoir, and so as to distribute the flood discharge evenly over the whole width of the tail channel. This channel form with a gentle longitudinal tail slope is best suited to soft soils, as thereby the severe action of an overfall on them is avoided.

FIG. 32

FIG. 33

SECTIONS OF DROWNED WASTE WEIRS

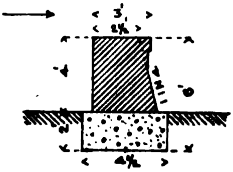




(ii) Drowned Weir (Figs. 32 and 33). This form is generally of small height, having its crest below the surface of the tail channel discharge when the reservoir is at high-flood level. The tail channel thus blocking the crest, the discharge is reduced below that of a clear overfall weir of the same length. When practicable and desirable, the drowned weir may be converted into a clear overfall one by deepening the tail channel so that its surface at high flood is just below the crest; even a less deepening of the tail channel will, by reducing the blocking by it, increase the discharging capacity of the weir. This form of drowned weir will be required when the levels necessitate it, and it also is useful for soft soils.

FIG. 34

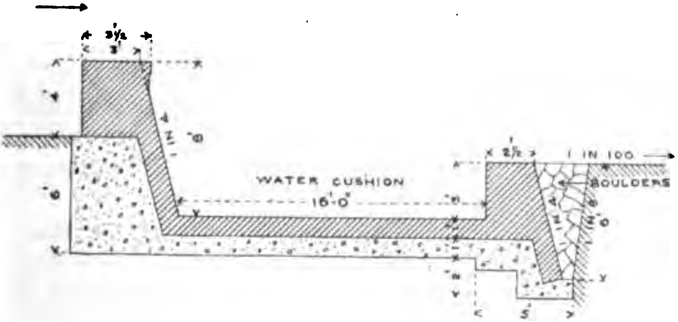
CLEAR OVERFALL WEIR



(iii) Clear Overfall Weir. This type is one having its crest always above the high-flood level of the tail channel. As for it the action of the overfall on the foundations is severe, the weir wall must be founded quite securely; for this reason it is best that solid unfissured rock should be available, and that the wall should be carried at least 2 feet into it (Fig. 34). Where such rock does not exist, the wall should be founded considerably deeper, and if the strata are readily erodible, a water cushion (Fig. 35) should be formed just downstream of the weir, and curtain walls, as may be necessary, built across the tail channel lower down. This form of weir

FIG. 35

CLEAR OVERFALL WEIR



having the greatest discharging power per lineal foot, is adapted to sites of restricted length.

(*d*) *Positions of Weirs.*—In respect to their positions waste weirs may be classed as—

(i) Flank weirs, at the immediate flank and in continuation of the dam embankment;
(ii) Saddle weirs, separated from the dam by high ground.

Flank weirs are the less safe form, as the discharge from them may outflank and injure the dam. To prevent this a wing wall is required on the upstream side, and a lining wall on the downstream side of the embankment (Fig. 36).

Saddle weirs discharge clear away from the dam, which therefore does not need protection, but to obviate the outflanking of the weir itself masonry flanks on one or both sides of it may be necessary.

(*e*) *Depth of Maximum Flood.*—The depth of the maximum flood permissible on a waste weir depends upon the nature of the foundations, and generally varies for a fair-sized reservoir from 4 feet to 6 feet. If the site is restricted in length, necessitating a greater flood depth, or if the foundations are inferior, a water cushion and curtain walls may be necessary to prevent scour. The shallower the flood depth, the greater are the length, and consequently the safety of the weir.

The smaller the flood depth over the waste weir, the lower will be the height required for the dam, and thus the cheaper will be the embankment. Comparative estimates of the combined costs of waste weirs of different lengths and dams of different corresponding heights should therefore be made, and other things being equal, the cheapest combination of the two should be selected.

(*f*) *Safety Flood Cuts.*—Where the ground at the proper level is sufficiently hard, an auxiliary flood cut may be excavated so as to assist the main weir in discharging an abnormal flood. That level may be about 2 feet below the calculated high-flood level; thus the cut will seldom come into action, and then only for a comparatively short time, so that it will probably not require protective works. It should be located, if possible, at the head of a small natural valley, and, anyhow, where its discharge will not cause damage; preferably its outfall should be to the tail channel of the waste weir. It should be of some length, so that even with a small flood depth its discharge will be useful in supplementing that of the main waste weir.

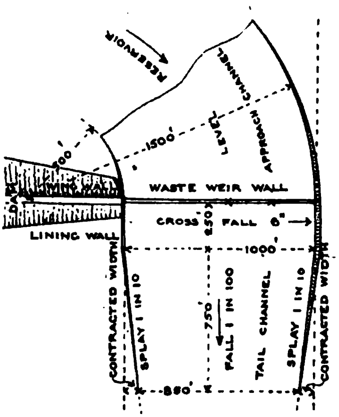
93. The Approach and Tail Channels.

(*a*) *The Approach Channel.*—This is usually excavated level with the crest of the weir, but where the channel is long and the water flowing over it would thus lose head by the friction of the bed, it is preferable to excavate it from 6 to 12 inches lower than crest level. The channel must have a perfectly clear and unobstructed course of the normal full width of the weir to avoid heading up in it. The effective discharging length of the weir is that measured normally to the line of flow (Art. 30).

Often the excavation of the approach channel of a flank weir may be decreased by curving it, as shown in Fig. 36. The curve should be a gentle one, so as not to make the water approach the weir crest irregularly, and should therefore be set out from a centre on the centre line of the dam some distance away from the waste weir flank.

FIG. 36

GENERAL PLAN OF WASTE WEIR



(*b*) *The Tail Channel.*—Where the weir crest is not well above the high-flood level of the tail channel, in order to prevent interference with the high-flood discharge of the former, that channel must also have a clear and unobstructed course of the full normal width for some distance downstream of the weir. Further downstream its width may be reduced (Fig. 36), when that will not cause the consequent heading up to extend above the weir crest, and thus reduce its discharging capacity. The amount of excavation may thus be considerably decreased, when the channel is long, and the floods confined to a comparatively narrow cut, which will tend to keep them in a defined course. It must be remembered that the contraction of the channel will increase its flood depth and velocity of flow. The latter should not exceed what the ground can withstand, either with or without protective works.

The tail channel should start from the weir at the calculated bed fall. To save excavation, this may be reduced as soon as such reduction will not cause heading up at the weir crest, but the high-flood level should be kept below ground surface so as to avoid expensive protective works, which will be necessary when it is above that surface. The channel should be led as soon as practicable into a natural drainage line in order to save excavation and secure a defined course.

For a flank or drowned channel weir it is desirable to divert floods from the dam by giving the channel a small cross-sectional fall—say, of 6 inches—away from the embankment. For a clear overfall weir little or no excavation will usually be necessary, as there will generally be a valley line below the weir. When a saddle weir is remote from the dam, a large amount of excavation is not required, but it will often be useful when the ground is soft to make a shallow and narrow cut below it to direct the first overflows, which will in course of time scour out a deep channel down to a hard stratum, and thus will confine floods to a defined course.

The effect of floods passing down a tail channel is generally to deepen, but not widen, it. The deepening usually results from the cutting back of the bed where the soil is soft. Even hard material may thus be removed rapidly. This action has been termed "the retrogression of levels" (Art. 116 (*b*)); when it occurs to a dangerous extent it should be stopped by the construction of curtain walls across the channel. The greater the slope of the channel, the higher the velocity of the flow down it, and therefore the slope has to be regulated so that that velocity may not cause much scour (Art. 36). For total flood depths not greater than 6 feet, where the ground is rocky the slope should not exceed 1 in 100; where the ground is hard, 1 in 500; while in ordinary soil it should not be steeper than 1 in 1,000. It must be remembered that in wide channels irregular erosion of the softer parts is likely to take place first and to lead to scour channels, which will concentrate the discharge, and thus tend to get deeper. This action should be stopped by filling the heads of the scours by large boulders, or, in bad cases, by constructing curtain walls across the tail channels, so as to distribute floods evenly downstream of them.

The best outfall for a tail channel is back into the stream on which the reservoir is constructed, and as near to the dam as is practicable without injuring the works or interfering with their drainage. The latter will occur if the detritus brought down by the channel blocks the drains from the dam. If the outfall is to another stream, that may not be able to pass off the added drainage without overflowing its banks. The bed of the original stream being then deprived of scour will, moreover, tend to silt up, and this may lead to the water-logging of its riparian land. The outfall should be curved gently to meet the natural channel downstream, so that its detritus will not block it, but will be carried down that drainage line.

94. The Outlet—General Remarks.

(*a*) *The Object of the Outlet.*—The outlet is the work by means of which the water in the reservoir is passed safely through, over or round the dam, so that it may be utilised for the purposes for which the storage has been effected. To ensure safety the outlet should preferably be founded on sound rock; if that is not available, on a sound, hard, insoluble stratum. Failing these, the foundations should be carried down deep, and should consist of a wide concrete base.

(*b*) *The Location of the Outlet.*—The outlet should be located at the most suitable site on the line of the dam, and the alignment of the head of the canal from it adjusted accordingly. For an outlet through a dam the best position is at the centre of a saddle, or depression, across the centre line of the embankment, as then the earthwork will settle symmetrically on both sides of it, and any underground percolation there may be will find its way to the depression, whence it can be drained away. The worst position for such a work is on steep sidelong ground, and particularly on the side of the river gorge, as there it will be unsymmetrical with the dam, the lower side of which will tend to move away from it, and the underground percolation, by lubricating the whole base downstream, will increase this tendency. When practicable, an excellent position is near a flank of the dam, or near a cross ridge from its centre line. In the latter case the approach bank to the outlet can be raised on natural ground, and not over the outlet tunnel, and will thus be independent of that.

In order to secure the best foundations, to cross the line of the puddle trench safely, and to prevent any settlement of the dam from affecting the outlet, it is best to have the top of the outlet culvert some depth below ground surface.

The culvert must never cross the puddle trench above its bed, as that would prove an unreliable foundation owing to its compressibility, and would thus lead to the fracture of the outlet. Where the ordinary foundations of that work are above the bed of the trench, the puddle must be replaced by masonry or concrete, so as to make a secure foundation for the culvert, and the two sections of the trench of different materials must have perfectly water-tight junctions. It is generally best to place the outlet on the side opposite to that on which is the waste weir, so that the canal will not have to cross the flood channel from the latter.

(*c*) *The Level of the Sill.*—In fixing this level it should be remembered that—

(i) Space should be provided below the outlet sill for the accumulation of silt in the reservoir—this space should be equal to about 10 per cent. of the gross storage capacity.

(ii) The capacity of the lower contours of a reservoir are relatively small to that of the upper ones. It is, therefore, generally not worth much extra expense to utilise the former by greatly lowering the sill.

(iii) The lower the sill, the greater will be the cost and the insecurity of the outlet.

(iv) The higher the sill, the quicker usually will the channel from the outlet gain command, and the shorter will be its course.

95. Varieties of Outlets.

(*a*) *Principal Types.*—The following are the principal types of outlets:

(i) Culvert under the Dam;
(ii) Headwall in the Centre Line of the Dam;
(iii) The Outlet Tower (or "Dry-well") in the Centre Line of the Dam;
(iv) Tunnel round the Dam;
(v) Headwall across an Open Channel outside the Dam;
(vi) Siphon over the Dam;
(vii) Pipe Outlet.

Of these Nos. (i) and (ii) are the ones generally built in India, and are described below. No. (iii) is practicable only for a dam with a masonry core wall (Art. 81 (v)); it tends to admit water into the heart of the dam. No. (iv) is the safest form, but is generally expensive; it is quite independent of the dam, a condition which some engineers consider to be essential for safety. No. (v) combines the advantages of No. (ii) and No. (iv), but is usually costly. No. (vi) can be used only for small discharges. On account of its liability to failure No. (vii) should never be used except for a very small and unimportant work. The pipes are apt to break or draw under the weight of the dam, and water may leak along them, or through their joints. It is also impossible to inspect the pipes after the dam has been raised over them. If pipes are necessary for a large reservoir, say, for a town water supply, they should be inserted in a culvert large enough to be traversed.

(*b*) *Culvert under the Dam* (Fig. 37).—The following remarks apply to masonry culverts, although iron and concrete ones are also built. As the culvert is buried under the dam, it is absolutely necessary to have it well designed and soundly constructed, otherwise failure of both works will result. Since the actual building takes place in the open, it can easily be supervised and properly executed. The foundations should be absolutely sound so as to give the culvert complete support throughout its length, and the precautions taken which are described at the end of paragraph (*b*) of Article 94. In England there have been failures of culverts because these were not observed.

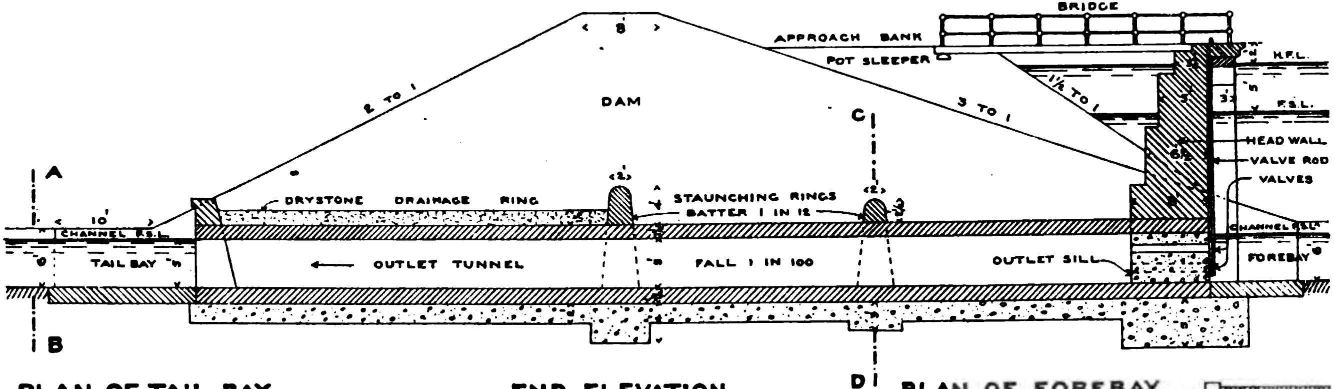
The trench excavated for the culvert should be considerably wider than the masonry, and should be taken out with sloping sides. The space not occupied by the culvert should be filled with good water-tight earthwork, so as to prevent leakage from the culvert from finding its way into the dam. Pure puddle in this position is objected to by some engineers, as they consider it increases the stress on the culvert, and may cause it to crack. The filling should be continued up to 2 feet above the crown of the culvert, so as to surround the culvert with a water-tight casing to prevent leakage through it. Above that level the remainder of the trench should be filled with the ordinary puddle trench material.

The section usually adopted for the culvert is an inverted ovoid, with the wide part as invert, so as to secure a broad

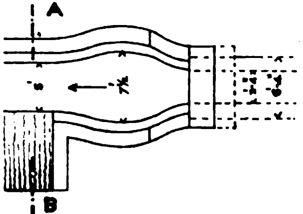
FIG. 37

OUTLET, HEADWALL AND APPROACH WORKS

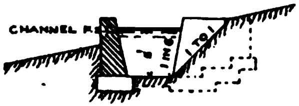
LONGITUDINAL SECTION



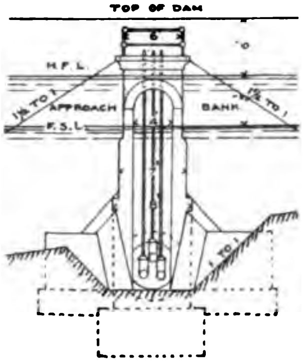
PLAN OF TAIL BAY



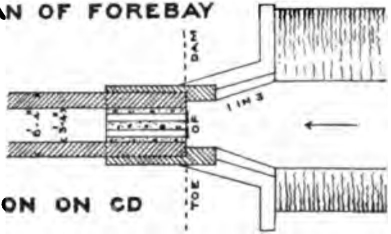
SECTION ON AB



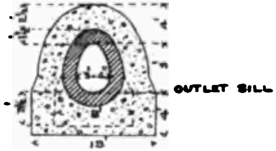
END ELEVATION



PLAN OF FOREBAY



SECTION ON CD



base and give the work the largest discharging capacity. The culvert should have a longitudinal slope of about 1 in 100 to facilitate drainage and the flow of the discharge. For the semicircular invert a flat pavement may be substituted. This should be constructed of large stones, laid parallel to the axis of the culvert, which should break joint, be well keyed under the arch ring, and should be set in cement mortar and founded on concrete. Staunching rings should be built on the centre line of the dam and upstream of this to prevent the creep of water. Downstream of the former the arch ring should be cased with dry stone for drainage purposes, and this should be surrounded with water-tight material so as to direct all percolation water straight out of the dam.

To carry the regulating works, a water-tight outlet tower, round or rectangular in cross-section, or a simple head wall should be built at the upstream end of the culvert, and access to it from the dam should be given by an approach bank and bridge.

(*c*) *Headwall on the Centre Line of the Dam* (Fig. 38).—This consists of a short length of masonry dam, or headwall, inserted in the embankment, and staunchly connected thereto by a long staunching wall on each side. At the ends of the headwall are four long wing walls (see also Fig. 12, p. 71), which preserve a passage for the water that is discharged out of the reservoir through sluices pierced in the headwall. The design is rather dearer than the ordinary culvert form, but has several advantages over that, as it can easily be inspected and repaired (being in the open), and can have a large discharging capacity which will aid the waste weir and allow the reservoir level to be lowered rapidly when necessary.

96. Maintenance and Repairs.

(*a*) *The Dam.*—During the construction of the dam careful observations by level and theodolite should be made at all high parts, and at such others where there may be any tendency to failure by motion. Levelled chainage stones should be fixed on the top of the dam along its centre line, and an annual record of their levels should be kept. The top should be maintained at its designed height, and any settlement that occurs should be made up before the next rainy season.

The drainage of the dam should be continuously attended to. Rain water should not be allowed to concentrate when flowing down the slopes, nor to lodge anywhere near the base of the dam, and all drains should be maintained free from obstructions, and their discharge recorded. The best test of the sufficiency of the drainage is that the ground downstream of the dam is dry.

The dam should be kept clear of long grass and shrubs, the latter being rooted out. The slopes should be maintained to an even surface so as to shed the rainfall regularly. Rat- and crab-holes should be dug out and the earthwork re-made. Cracks should be filled by ramming into them a gritty and clayey mixture by means of chisel-pointed poles. A permanent gang of some strength should be employed for the first two years in making up cracks, settlements, and rain scores, and should thereafter be reduced as found necessary.

The pitching should be examined as the water level falls, and all loose stones, settlements, and other defects made good by a system of continuous repair. All shrubs should be rooted out.

(*b*) *The Waste Weir.*—The masonry of this and the outlet should be pointed, repaired, and underpinned as may be necessary, and all plants growing in it rooted out. All scour channels in the tail channel near the weir should be prevented from cutting back towards it, and the approach channel should be maintained free from obstructions to flow.

(*c*) *The Outlet.*—The culvert should be examined twice a year, and all repairs should then be carried out. The valves, their seatings, and their rods should be examined and attended to when the water level is at its lowest, all parts in working contact greased and others painted. The ironwork of the approach bridge and headwall should be kept well painted, and the woodwork tarred, and any settlement of the approach bank should at once be made up.

(*d*) *The Reservoir.*—The land boundary marks should be inspected and maintained. Plantations should be attended to and extended by the guards employed. Observations of rain-gauges in the catchment should be made daily and recorded; daily records of the reservoir level and outlet discharge should be kept; flood observations should be made, and observations to test the loss by evaporation and absorption should be carried out.

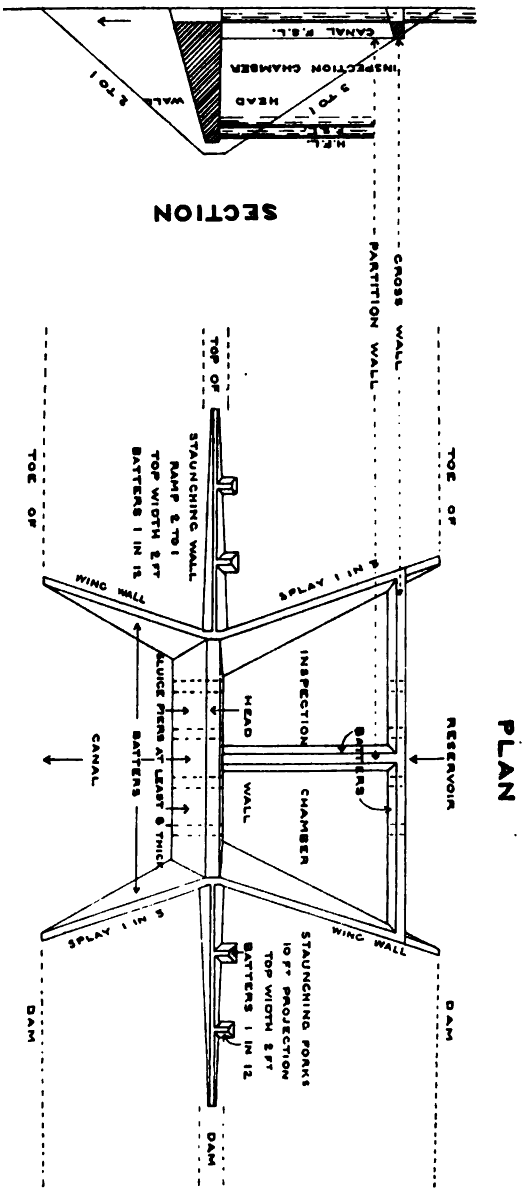


FIG. 38

HEADWALL IN CENTRE LINE OF DAM

CHAPTER VIII.

MINOR RESERVOIRS AND WEIRS.

97. General Remarks.

(*a*) *Description and Advantages of Small Irrigation Systems.*—In Ceylon and in parts of India, chiefly in Madras, there are numerous old native reservoirs, locally known as "tanks," which are mostly utilised for growing rice, and in Bombay, on streams with small perennial flow, old native intake weirs, there called "bandhárás," under which perennial and garden crops are cultivated. These small systems in the aggregate irrigate a very large area. Such works are left ordinarily to the cultivators to manage in regard to the distribution of water, but generally are kept in repair by Government agency. With respect to distribution the old native system of apportioning water by shares (Art. 1 (*d*)) is usually in force, and, in Ceylon in particular, the lower fields are watered before the upper ones, which ensures the fairest and most economical division of the supply (Art. 23 (*c*)). By the construction of the tanks each group of irrigators is given an independent source of supply, allocated to a settled area, all of which is entitled to water at the same rate of distribution. The total amount available is stored close to the irrigable lands, and so far as the vagaries of the rainfall permit, is in sight and known. The conditions under the bandhárás are similar, except that the water is not stored in sight, and the probable amount and duration of the flow supplying the channels have to be judged by experience from the character of the rainfall.

(*b*) *Objections to and Expansion of Systems.*—The main objection to this system of old works is that the irrigators under them consider they have a prescriptive right to all the water available, and they will therefore not economise its use so as to extend the benefits of irrigation to new lands; thus the irrigated area does not increase as it should do in consequence of more scientific methods of distribution and better upkeep. As the most favourable sites for works were utilised by the old constructors, and as, anyhow, the construction of similar new works by paid labour is very expensive, any great extension thereby of irrigation is not likely to take place. That can best be ensured by the improvement of the old works, chiefly by increasing their storage when practicable, but before this is undertaken it should be arranged that the total supply will be liable to control to enable it to be expended to the greatest benefit of old and new irrigators.

(*c*) *Administration.*—In administering such an area of old irrigation with a view to keeping the systems in repair, and to improving and, if possible, to extending them, it is necessary to apply the principle of hydrographic districts (Art. 3) by dividing the country into basins and minor basins, and the works therein into groups and sub-groups. Each division should be studied as a whole, and the repairs required and extensions feasible should be carried out on a comprehensive plan, so that the total catchment area may be utilized in the best way, and so that works may be constructed most economically in regard to cost and the staff required for their execution.

98. Advantages and Disadvantages of Small Works.

The principal advantages of these small works are as follows:- They utilise isolated and small catchments which cannot be included economically in large schemes. As with them the irrigable area is close to the source of supply and is compact, the loss in transit is small, and thus the duty should be high. It is usually near the village, and is thus conveniently situated to the irrigators. Moreover, in a connected group, especially in the case of bandhárás, there is a considerable amount of seepage from the upper to the lower works, and thus water can be used more than once. The distribution can be managed locally by the irrigators themselves, and with the minimum of outside administrative interference, which will be required only to ensure fairness.

The chief disadvantages of such works are the uncertainty of replenishment and supply; the large area occupied by water in the tanks involving an extensive loss by evaporation, and the diminution of the amount of fertile land in the valleys; the extra cost of maintenance of numerous headworks, which are peculiarly liable to damage by floods; and the extra cost and difficulty of supervision for maintenance and administration.

99. Improvements to the Systems.

(*a*) *Increasing Storage and Yield.*—The first improvement generally required to an old tank is to increase its utility by enlarging its storage capacity. If the natural catchment is sufficient for this, all that is necessary is to raise the full-supply level of the works. If it is insufficient, it should be increased by the construction of feed channels, care being taken, of course, that this is not done to the detriment of lower works. The feed channels will usually be small, and will then simply divert surface drainage into the tanks. Where, however, they cross small watercourses, it may be advisable to construct auxiliary tanks thereon (Art. 69 (*b*)). In Ceylon there were in ancient days several very large feed channels, each of which supplied numerous tanks in the low dry parts with water from streams and large reservoirs in the hill country where the rainfall is certain and abundant (Art. 69 (*d*)).

Works in operation probably occupy the best sites, and the people under them are skilled in irrigation. The development of such works should therefore be the first improvement undertaken. New works in the neighbourhood should follow, and, finally, new works in new areas.

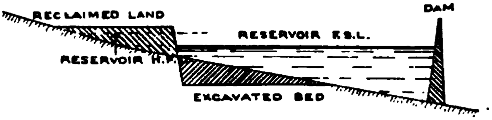
(*b*) *Development of the Supply Channel System.*—A more drastic improvement will be to abolish the tanks and supply the irrigable area by direct flow from neighbouring streams, if these have sufficiently prolonged and ample discharge. By this means the great loss from evaporation will be avoided, more fertilizing silt will be carried on to the fields, the cost of maintenance will be reduced, the country will be rendered more sanitary by getting rid of the tanks (which in this respect may be regarded as malarious swamps), and a considerable area of previously submerged most fertile land will be reclaimed for cultivation. The objections to such a complete remodelment are that it involves a large alteration of the long-practised system of irrigation, and loses the benefits of storage and utilisation of seepage. Probably the best form of improvement when practicable will be to maintain the tanks at their existing size, or reduce that somewhat, and to supplement them by feed channels having considerable flow. Thus will be obtained the advantage of more certain and earlier replenishment and a largely increased supply, which can be utilised for irrigation under the old system of distribution, and without diminishing the valuable irrigable area in the valleys.

Interdependence on each other of minor tanks is inadvisable. If additional supply is required, each tank in a series should obtain it independently from a main feed channel.

(*c*) *Remodelling Tank Basins.*—Another form of improvement was suggested some years ago in Madras, but it is not known if effect was given to the proposal. This consisted in the remodelment of individual tanks by excavating the shallow high parts of their beds and utilising the spoil to raise and thus reclaim the land near their margins (Fig. 39). By this plan the average depth of the tank will be increased and evaporation thus reduced, while the culturable area will be increased and marginal swampy land rendered sanitary. It is, of course, a matter for estimating to determine whether the cost of the improvement will be justified by its results. In India it will doubtless often be possible thus to remodel a tank as a famine relief work, and that form of employment will have further advantages from an administrative point of view by providing suitable labour for the agricultural population near their homes. The areas in which tanks are situated are, however, seldom visited by scarcity.

FIG. 39

REMODELLING TANK BASIN



(*d*) *Improvement of Village Water Supply.*—When a tank is near a village it is generally utilised for the water supply of the inhabitants and their cattle. Owing to its usual shallowness the storage often does not last throughout the year on account of the excessive evaporation to which it is subject. Moreover, the supply being derived from a more or less contaminated gathering ground, and not being conserved, is insanitary. An improvement, small in itself, but of considerable value, would consist in excavating a deep pond in the tank bed, and raising the dam with the spoil. This pond would be useful for watering the cattle, for which purpose it should be dug with comparatively gentle side slopes, and have an approach road sloping, say, at 1 in 10. It should be located some distance from the dam to prevent damage thereto, and should not be deepened so as to lay bare porous strata. For the requirements of the inhabitants a small well could be excavated on the downstream side of the dam and opposite to the deepened pond, so as to get naturally filtered water. The well should be steined and provided with a pulley for lifting the water, and near this the ground surface should be paved and a gutter led off to drain it.

(*e*) *Bandhárá Improvements.*—The improvements to bandhárá systems will generally consist in the provision of good head regulators, scouring sluices, and cross-drainage works, and in betterment of the alignment and cross-section of the irrigation channels. It will seldom be possible to increase the supply, except in the rainy season, as the existing demands generally exhaust the water available, especially towards the end of the fair weather. The irrigators often request that the bandhárá should be raised so as to enlarge the storage capacity of its backwater pool, but this measure is seldom advisable owing to the fact that the sand brought down by the stream will soon reduce the temporarily increased capacity to its original amount. The provision of removable wooden weir crests with the object of increasing storage is also generally inexpedient on account of its cost and difficulty of management by the irrigators themselves.

100. Yield of Catchments and Storage.

In the case of small tanks it is naturally not possible to have long-continued scientific observations made of the amount of yield which can be impounded. Some dependence may be placed on local statements of how the tanks fill, but it must always be remembered that the irrigators attach more importance to having their supply increased than to making their works structurally and hydrographically secure, and are therefore inclined to exaggerate the yield of their catchments. When an increase of storage is contemplated, it will therefore be advisable to subdivide the catchment roughly into areas, each having a distinctive rate of probable yield, and to apply to them coefficients of that yield with reference to the rainfall registered at the nearest gauging station. The coefficients can approximately be arrived at from what is known to occur on similar neighbouring catchments, and the resulting estimate of yield can be compared with the local idea thereof. A somewhat liberal allowance may be made so that the tank may be able to store the yield of years of good replenishment. (See also Art. 103 (*b*)). It must be remembered that the full-supply storage capacity of the tank need not be equal to the average yield of the catchment, as the tank can fill more than once, seeing that its contents are drawn upon for irrigation during the rainy season.

New tanks are not required where sufficient flow is available throughout the irrigating season from a neighbouring stream; if, however, that flow is liable at times to be too small, storage will be desirable to make up its then deficiency. New tanks should be located where their natural catchments will produce an abundant and certain run-off just before and during the irrigating season. It is better for them not to have recourse at first to aid from feed channels when this can be avoided; such can be kept in reserve until the extension of irrigation calls for their construction.

101. Repair of Tanks.

The guiding principle to be followed in repairing these small works is that the design, without being extravagant, must be quite secure in all probable events, and must be such that the works can safely be entrusted to the irrigators for ordinary maintenance. When designing the repairs their cost has to be considered with reference to the amount of the annual revenue from the work. In Bombay the limit fixed for expenditure is ten times the annual revenue, and is not to be exceeded without special sanction, which is given after the distinctive circumstances of the case have been reported and admitted. It should be noted that risks should not be run in order to keep within the prescribed limit of cost; all that should be done in this respect is to effect safe economies, and to omit such sub-works which, although desirable, are not absolutely necessary for safety.

Repaired tanks should be examined as often as practicable, and invariably at the close of the first monsoon succeeding the completion of the repairs, so that any damage done may at once be made good, and so that any defects of design may be remedied. In order to provide funds for such petty repairs and alterations, a small provision for monsoon damages should be entered in the original estimates and devoted exclusively to making them good.

A difficulty which arises when the full-supply level of a tank is to be raised is in connection with the consequent submergence of valuable marginal land, which, if thus thrown out of cultivation, has to be acquired at considerable cost. It is usually considered that damage is not done to rice lands if they are submerged not more than 1 foot at full-supply level, as by the time the water attains that level the crop will be well advanced. In such cases the marginal land need not be acquired if the owners are willing to retain it in the altered conditions, and to this they generally agree rather than surrender it.

All tank property and all land acquired should be demarcated permanently, and encroachments should be prevented. To prevent damage to the dam a narrow strip of land downstream of it should be taken up.

102. Repair of Dams.

(*a*) *Design of Dam.*—(i) The cheapest safe combination of dam and waste weir should be adopted. It should be remembered that a long weir with small high-flood depth is safer than a short one with large high-flood depth, as any abnormal increase of the high-flood depth will give the former weir greater discharging power than the latter.

(ii) The earthwork to be added to the dam should be disposed so as to involve the minimum expenditure, and so as to get as good an alignment as possible. Care should, however, be taken when practicable to avoid placing thin veneers of new earthwork on the old dam, especially on the upstream slope, as they will have a tendency to slip. Such veneers when unavoidable must be well benched on to the old embankment. Rough trial estimates of different alignments should first be made, and from these the most suitable plan should be selected.

(*b*) *Cutting off Arms of Tanks.*—Many old tanks have long narrow arms on either one or both flanks where the storage ponds up tributary valleys. As the works are constructed the high-flood level is the same in the arms as it is in the main part of the tank, and the dam for its whole length has to be raised to the same level above it. To effect economy in reconstruction the arms are often cut off by cross banks, when this does not entail an extensive reduction of the catchment area and storage capacity. When, however, the capacity will be considerably diminished by cutting off the arm, this work may often be carried out without loss or danger (should the tributary catchment be small) by inserting at a low level a pipe in hard ground near and through the upstream end of the cross bank, or in a cut outside it. This will preserve the original catchment and storage, but will retard the rise of floods in the arm, or arms, during floods, so that the embankment flanking them need not be raised so high as the dam opposite to the main part of the tank. Even should the flood rise excessively in the arm and breach its bank, the damage done and loss of storage thus incurred will be small on account of the main tank being cut off by the cross bank.

(*c*) *Top-Width.*—For ordinary dams the top-width should not be less than 6 feet; for those carrying roads on top the width should not be less than 12 feet. It is preferable in the interest of safety, both of the work and the traffic, that a road should not be carried on top of a dam, but along and near the base of its downstream slope. This, however, causes the dam to occupy extra land, but the additional strip will be only 4 feet if the width of the roadway, protected as it is on one side by the slope of the dam, is reduced from 12 feet to 10 feet, and the top of remodelled dam made 6 feet instead of 12 feet in width.

(*d*) *Free-Board.*—The vertical height of the top of the dam above calculated high-flood level should not be less than 2 feet. The objects of this extent of free-board are to allow for settlement and wear by traffic over the dam; to provide against any abnormal rise of the surface of the tank; to prevent cracks on the top of the dam from passing below high-flood level; and to increase the thickness of the dam at and below high-flood level.

The sanctioned top level of the dam should be permanently marked by header benchmark stones fixed in it at intervals.

(*e*) *Side Slopes.*—For dams less than 10 feet high the upstream slope should be 2 to 1, and the downstream one 1½ to 1 throughout. For higher dams it will be advisable to flatten both these slopes by ½ to 1 below that height from the top.

(*f*) *Casing.*—Where the new embankment is formed of soft material, the slopes and top of the dam should have a 6-inch thick casing of binding muram or gritty soil.

(*g*) *Metalling.*—Where the top of the dam has to be protected from wear by considerable traffic over it, it should be covered by a coating of metal 4 inches thick, or one of hard muram, etc., 6 inches thick, laid on the casing and well consolidated. The coating may be finished off with a layer of sand blindage 1 inch thick.

(*h*) *Pitching or Turfing.*—Where erosion of the upstream slope by wave-wash is likely to take place, that slope should be protected by pitching or turfing, as the case may require, and this should be carried up at least to full-supply level, and preferably to 1 foot above that.

Pitching should consist of single stones not less than 9 inches thick, laid on a 6-inch layer of quarry spauls, etc.

Turfing can be cheaply done by planting on the slope chopped "harali" grass roots, or sowing grass seed just before the monsoon. The base of the downstream slope might similarly be turfed to prevent its being guttered by rain. It is also made by means of sods cut to rectangular dimensions, laid with their edges close together, beaten gently with rammers, and watered till the grass sprouts.

Wave-wash need not be feared, nor guarded against, if—

(i) The "fetch" is small;
(ii) The water surface is protected from the action of the wind by the growth of reeds, etc;
(iii) The dam is to the windward side of the tank;
(iv) The surface of the earthwork of the dam is sufficiently hard to withstand wave-wash.

(*i*) *Puddle and Key Trenches.*—Ordinarily, a puddle trench is not required, but one is advisable under the upstream toe when the thickness of the new strip of embankment is considerable, or the old dam leaks. Such a trench may generally be made 3 or 4 feet deep, with a bottom-width of 3 or 4 feet, and side slopes ½ to 1. It should have an earth cover as thick as possible over it, i.e. it should be placed as much downstream as practicable, but not beyond the centre line of the dam.

When extensive breaches have to be repaired, it is desirable to have a puddle trench along the centre line of the base and slip tongues or trenches (see Fig. 93, p. 383) up the slopes. The filling of the breach should be carried up about 1 foot above the ordinary top level of the dam, so as to make the repair the safest part of the whole work.

If the top of the old dam will be below the calculated new high-flood level, a key trench, say, 3 feet bottom-width and 2 feet deep, should be excavated along its centre line, and this should be carefully filled with good earth well consolidated.

(*j*) *Construction of Earthwork.*—The general principles of dam construction (Chapter VII) apply to the execution of the repairs of these minor works, but naturally on account of their smaller importance and size so much care is not required as in the case of major works. The surface of the old dam and of the ground underlying the new earthwork should be cleared of all vegetation, rubbish, etc., and should be roughened, and the slopes excavated in steps just before the new embankment is formed against them. The lines for the new toes should be lock-spitted, and the section of the work set out at intervals of from 25 to 50 feet by profiles of bamboos and strings, so as to include the allowance for settlement, which is often taken as 1 inch to a foot. The spoil for the dam should be excavated from the silted tank bed, and the borrow pits not allowed to extend to within 40 feet of the embankment, nor to go down to original ground level. The work should be carried up to the full width in 6-inch layers (which in the case of thin added strips should be normal to the outer slope), all clods and lumps broken up, and the earthwork consolidated by means of rammers.

103. High-Flood Discharge.

(*a*) *General Remarks.*—Small tanks utilised chiefly for growing rice are frequently situated in areas visited by rain which falls in numerous small showers rather than in a few heavy downpours. These areas often have flat valleys extensively terraced for rice cultivation and minor tanks, and do not contain much land with steep slopes ; moreover, the surface consists of absorbent soil of some depth. These conditions are against the production of sudden high floods, but for that of long-continued small floods, so that a large provision for waste weir discharging capacity is usually unnecessary. For the same reasons it is best not to reduce that capacity by allowing for flood-absorption in the tank during its rise from full-supply to high-flood level. Where there are other tanks in the catchment, they will exercise a moderating influence on its high-flood discharge according to the proportion which their areas at full-supply level bear to the extent of their individual gathering grounds. Thus a tank with a large water-spread and small catchment will absorb most floods when rising from full-supply to high-flood level, while a storage with a small surface area and large gathering ground is likely during heavy rainfall to attain high-flood level early, and thus subsequently not to be able to diminish the spill rate of discharge of the run-off entering it. Such connected tanks introduce the danger that the failure of an upper one may entail the breaching of the lower ones by the extra flood thus produced. To meet this increased waste weir discharging capacity or the provision of safety cuts (Art. 92 (*f*)) and breaching sections (Art. 83 (*g*)) is necessary. This danger is all the greater in the case of such small tanks, as some of them may be out of repair, and most of them are not supervised professionally.

(*b*) *Estimation of High-Flood Discharge.*—The best way to estimate the ordinary high-flood discharge is to divide the catchment roughly into areas of similar flood-producing capacity, and to apply to each a coefficient of run-off, so as to arrive at the "equivalent catchment" area which will give the same discharge at the assumed standard rate of run-off. Thus the relative rates of run-off might be taken for—

Class I, steep hilly slopes	4·00
Class II, hilly country with moderate slopes ..	2·00
Class III, ordinary plain country..	1·00
Class IV, terraced rice lands	0·50
Class V, tank basins in catchment	0·25

The equivalent catchment area would be calculated thus:

Minor Tank.	Class of Catchment Area.					
	I.	II.	III.	IV.	V.	Total.
	Actual Catchment in Acres.					
No. 1	20	30	50	100	8	208
No. 2	30	60	100	300	20	510
No. 3	—	—	—	500	52	552
Total	50	90	150	900	80	1,270
Coefficients	4	2	1	½	¼	—
Equivalent catchment area in acres	200	180	150	450	20	1,000

The proper standard rate of run-off and the coefficients to be taken into account should be determined from the actual results of as many typical tanks as possible. For this purpose the high-flood levels of tanks should be ascertained correctly as soon as practicable after they have taken place, and should thereafter be engraved on the flanks of the waste weir walls with the dates of their occurrence.

104. Design of Waste Weir.

(i) If the tank is supplied by feed channels, their calculated high-flood discharges should be added to that of its natural catchment.

(ii) The length of the waste weir should be as great as is economically possible, so as to reduce the high-flood depth as much as practicable. That depth should ordinarily be restricted to 2 feet, as shallow floods have a less scouring power than deep ones. For quickly determining the length a table should be prepared of waste weir discharges per foot run at various depths differing by $\frac{1}{10}$ of a foot.

(iii) Drowned waste weirs or channels are to be preferred to clear overfall weirs, as they will cause less scour.

(iv) The waste weir should preferably be placed at the flank of the dam and where the foundations are good. As a general rule it is better to have only one waste weir, and to avoid making one in the centre of the length of the embankment, so that access to the dam may be facilitated, not only during floods, but also in the fair weather. The nature of the foundations should always be noted on the drawings, and should be determined by one or two small trial pits, the sections of which should be given on the plans.

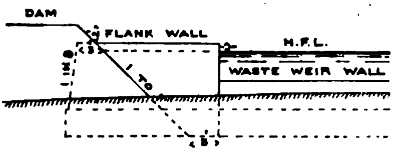
(v) The crest of the waste weir should be formed of rough-dressed headers set in hydraulic mortar and laid parallel to the flow, so as to offer the maximum resistance to displacement. When the high-flood depth is 1 foot or less, and the soil is hard, a simple masonry crest 2 feet wide and 9 inches thick without foundations should suffice, or a concrete bar 2½ feet wide and 12 inches thick might be formed across the waste weir channel. The advantage of a permanent crest is that it fixes the designed full-supply level, and thus shows if that is being lowered by a scour channel or being raised unauthorisedly to the endangerment of the dam.

A design for a pitched slope waste weir is described in Article 131.

(vi) The flank wall of the waste weir next the dam should be continued into the earthwork for a length of at least 3 feet at high-flood level. The waste weir crest should commence at a point where a vertical line through it will not be less than 3 feet from where the end slope of the dam produced will cut the foundation of the crest wall. The end slope of the dam may be reduced to 1 to 1, and the conical end of the dam and 5 feet of the longitudinal slopes next to it should be pitched on both sides (Fig. 40).

FIG. 40

WASTE WEIR FLANK



(vii) The other flank of the weir should ordinarily be run 3 feet into the natural ground at high-flood level after the side of the approach and tail channels has been excavated to its designed slope. If, however, the ground consists of soft or porous soil, the flank should be run at least 5 feet into the slope to prevent its being turned.

(viii) Flank walls should be raised at least to 1 foot above high-flood level. When, however, there is a safety waste weir at a flank, the top of the wall there should be level with the sill of that weir.

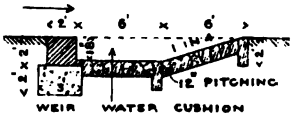
(ix) Whenever there is some doubt as to the discharging capacity to be allowed for the waste weir proper, and whenever the levels permit of its economical construction, a safety waste weir should be excavated. Its sill should be a little below high-flood level, and its length should be sufficient to enable it to afford substantial assistance to the main weir during abnormal floods (Art. 92 (*f*)).

(x) The approach channel to the waste weir wall should be unobstructed and of the full width of the weir. If the channel is a long one, its bed should be lowered, say, 6 inches below full-supply level, so as to reduce the frictional loss of head of the water flowing over it. The tail channel should have an unobstructed course of the full width of the weir for some distance from its crest, and may thereafter gradually be lessened in width. It should meet the natural outfall channel tangential to its flow. Neither of these channels should curve too sharply to or from the weir crest, so that the flow of water over that may not be retarded, or be made irregular, by having to change its direction suddenly.

(xi) A water cushion should be provided where much scour is likely to take place below a waste weir. A simple pitched water cushion, as sketched in Fig 41, will suffice when the depth of flow and probable depth of scour are small; where extensive scour may be expected, the crest wall should be founded deep and a masonry cushion provided (Fig. 35, p. 197).

FIG. 41

PITCHED WATER CUSHION



(xii) Where the waste weir is a simple channel, a benchmark stone should be fixed to indicate its true level, so that that may be preserved (see (v) above).

105. Outlets.

(*a*) *General Remarks.*—Many small tanks have open cuts for outlets, and these when out of use are closed by embankment, which is liable to leak or breach. Other old works have indifferent outlets which leak. In all cases proper outlets are a considerable improvement, and in many a necessity, but, unfortunately, they are expensive. Partly on account of their cost, and partly because they form weak points in the dam, the outlets should be as few in number as practicable. They should preferably be located in cutting, and they should be founded as securely as possible. The junction of the earthwork of the dam with them should be most carefully made, so as to be quite water-tight. The outlet culvert should be laid with water-tight joints, and should have a staunching ring at its centre, where a short surrounding puddle wall should be formed in the dam. Certain forms of outlet are described shortly below. As a comparison of their costs are quoted their estimated amounts calculated at the same rates of construction.

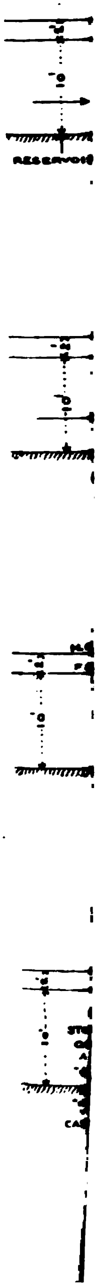
(*b*) *Forms of Outlet—No. I—Dharwar Pattern* (*A*)—10 *Feet Head—Rs.* 460 (Fig. 42).—Across the downstream end of the inlet chamber are built two cross walls to form inlet wells; these are roofed over with stone slabs, which are pierced by conical holes, and these are closed by wooden plugs fixed at the ends of lifting poles. A short length of puddle wall is formed along the centre line of the dam to embrace and overlap the staunching ring (Fig. 50), built around the outlet slab drain. These are to secure a water-tight junction of the outlet with the dam.

No. II—Dharwar Pattern (*B*)—10 *Feet Head—Rs.* 510 (Fig. 43).—In this design, instead of the small inlet wells, a single cast-iron tee pipe is fixed at the base of the downstream wall of the inlet chamber. The vertical limb of this is closed by a wooden plug worked by a pole fixed to it, and the horizontal limb at the base by a similar plug worked by hand when the tank level falls. In the figure has been shown a rear chamber with watercourses taking off from it at different levels; this device can, of course, be applied to other designs. The objection to it is that when the highest watercourse is flowing, the whole of the slab drain under the dam is full of water, which may pass into the earthwork and cause a leak or a breach, if it is not solidly constructed.

No. III—Belgaum Pattern—10 *Feet Head—Rs.* 365 (Fig. 44). —A headwall is built clear of the dam, and is reached by an approach bank and foot plank. The chief advantage of this form (which is also shared by designs IV, VI, and VII) is that the central puddle wall and staunching ring are removed to the maximum distance from the tank, and thus infiltration is reduced. Another advantage is that expensive wing walls are not required. The approach bank should be made of dry material, and should be carefully pitched all over, so that it may stand with its steep side slopes of 1 to 1. The foot plank should be bolted down at its ends to make it steadier and to prevent its removal.

No. IV—Dam Slope Outlet—10 *Feet Head—Rs.* 275 (Fig. 45). —The inlet is formed by a cast-iron vee pipe embedded solidly in masonry, which is continued to form a guide bed for the upper wooden plug, and also a stop for it. The vee might be dressed in the masonry itself at a saving. The space between the front and rear walls of the guide chamber should be as short as possible, and sufficient only to enable the plug to travel and to be taken off when necessary. A grating is fixed over this chamber to prevent the entry of rubbish.

The plug closing the upper branch is fixed to a pole, which travels up the slope of the dam through guide stones bedded on bed stones, laid on well-packed muram to prevent settlement. Any adjustments of the guide stones necessary should


RESERVOIR

at once be made, especially after the first monsoon. If desired, the pole can be of 2½-inch galvanised iron pipe. The lower plug is worked by hand when the tank level falls.

The advantage of this design is that it dispenses with a high headwall and wings, which are expensive.

No. V—Headwall in Centre Line of Dam—Head 6 *Feet—Rs.* 360 (Fig. 46).—In this form a headwall is built in the centre line of the dam, and a cast-iron tee outlet pipe is fixed at its base. The discharge passes through this into a simple pitched channel between the two conical ends of the dam. The top of the headwall is widened out as a 3-foot coping, so as to form a footway.

The great advantages of this design are that practically everything can easily be inspected, and there is no culvert under the dam to silt up or let water into the embankment. The disadvantage is that the tank water is admitted to the centre line of the dam. On account of this the flanks of the headwall should be run for some distance into the embankment, and should be carefully surrounded by puddle, which should be continued for some feet as puddle walls beyond them.

The design can be used for all ordinary heads. A similar one for a head of 10 feet will cost about Rs. 900. The amount will, however, be considerably decreased if the wall is built in cutting at a site where the ground is hard and its level high, as then the foundations of the flanks can be stepped up and those walls made thinner.

No. VI—Outlet Tower—10 *Feet Head—Rs.* 510 (Fig. 47). —This design, like those of Nos. III and IV, has one tee inlet at the base without wing walls, but also has two or more upper inlet vents in it at different levels, which facilitate working. The drystone approach bank is brought right up to the tower, and thus a foot plank is not required. The drystone should be carefully bonded together.

Instead of tee iron inlets, simple holes can be formed in the side walls at small vertical intervals, and these can be controlled by wooden plugs worked by hand. By removing these in succession under a similar head, a fairly regular discharge can be obtained, which is an advantage when the amount of flow has to be constant. This arrangement will lead to a saving of about Rs. 50 on the estimated cost. With several controlled inlets the discharge can be increased when desired.

No. VII—Dwarf Headwall—5 Feet Head—Rs. 110 (Fig. 48). —This design is adapted for small heads, for which the plugs can be removed by hand; the upper plug, as shown, might have a short pole fixed to it. It is not necessary to go to the expense of inserting a cast-iron tee pipe in the headwall, as the inlet holes can be formed in the masonry.

(*c*) *Details of Designs.*—In most of the designs there are two inlet openings, the upper of which can be worked from the top when the tank is full, and the lower of which is placed at the level of the bed of the tank, and is controlled directly by hand, when the water has fallen to 3 feet or less above that bed. When the inlet opening is formed in the masonry, it is dressed to a small taper, but it is best not to taper the closing plug, as then it is liable to jam. The plug is therefore made cylindrical with shoulders at the top (Fig. 49) to avoid jamming. This advantage is gained at the expense of a little leakage.

In the Dharwar patterns (Figs. 42 and 43) the outlet slab drain has a vent 2 feet high and 1½ feet wide (Fig. 50), which enables it to be cleared of silt without difficulty. The side walls, 1½ feet thick, are carried down below pavement level. To make the slab drain water-tight when flowing full it is best to continue the side walls 6 inches above the top of the slab, and to cover that with concrete; such covering is required only for the upstream half of the drain. The Belgaum pattern (Fig. 44) has a vent 1 foot high and 1½ feet wide, and is less easily cleared of silt. The side walls are only 1 foot thick, and the surface of the pavement is at the level of their base. This type is cheaper than, but inferior to, the Dharwar ones.

Pipe drains (Fig. 51) can be made of 6-inch glazed earthenware set in concrete 9 inches thick, or might be moulded directly in concrete on a cylindrical wooden pattern cut diagonally in two longitudinally, so that the halves may be drawn out when the concrete has set. Pipes may be made of thin sheet iron, or cast iron, and cased with concrete, or of reinforced concrete. In Ceylon tapered concrete pipes about 2 feet long are formed in iron moulds, and the pipe line is made by fitting the narrow end of one length into the wide mouth of the one downstream of it. This leads to a rough pipe, which retards flow, and the numerous joints are apt to leak. The head on pipes being usually considerable, they should not choke with silt; if they do, they can be cleared by a bamboo, to the end of which a cutting edge is fixed.

The approach steps should be laid header-wise, so that they may not get displaced by the settlement of the dam.

The designs can be varied by adopting for other types different portions of the types described. Thus a concrete pipe can be substituted for a slab drain, and a slabbed inlet for a tee-pipe one.

106. New Bandhárás.

(*a*) *General Remarks.*—The old irrigators were experts in devising systems of irrigation suitable to the natural conditions of their localities. Generally speaking, in districts where bandhárás do not exist, new ones are not likely to be successful. Monsoon irrigation might, however, be developed on streams which have continuous flow during that season, although they dry up soon afterwards. If a stream has only a negligible discharge soon after the cessation of rainfall, it cannot directly be utilised in this way, as irrigation will not be required during rainfall, and will not be practicable thereafter. Flood irrigation (Art. 7) is that which is practised with short-lived flow. It is, however, adapted to areas where there is scarcely any rainfall.

(*b*) *Favourable Conditions.*—The following are the conditions favourable for the construction of a bandhárá, and for irrigation from it :

(i) The stream, which is the source of supply, should have a discharge of amount and duration sufficient to bring to maturity the crops to be irrigated.

(ii) The bed of the stream should have sound rock at or near the surface, so that the cost of founding the bandhárá may be small, and so that its foundations may be secure.

(iii) The natural high-flood depth and the height to which supply has to be raised should both be low, so that the bandhárá will be of some length; but being low, and having low flanks, will probably be less costly than a short, high structure, and the action on its foundations will be less severe than in the case of the latter.

(iv) The banks of the stream downstream should not be precipitous above crest level, or it will be difficult to construct the head section of the irrigation channel. They should rise pretty steeply to high-flood level, and thereafter gently, to facilitate the construction of that section.

(v) The longitudinal fall of the stream and of the country should be fairly steep, so that the irrigation channel may quickly be led out of the high-flood margin and may itself soon gain command. The best site for a bandhárá is thus generally a little above the head of a rocky rapid or fall, but not too close to it, so that the work may not be subjected to high velocities in floods.

(vi) The irrigation channel should not cross any important drainage lines, so that costly cross-drainage works will be unnecessary. It is thus often advisable to place the bandhárá close downstream of the junction of a large tributary with the main stream.

(vii) The area to be irrigated should be of fair size, nearly level, fertile, and well drained, but not traversed by many nor deep watercourses. It should be compact and near the bandhárá so as to lessen the cost of the irrigation channel and the loss of water in transit down it. It should not be far distant from the village concerned, so that the irrigators may easily cultivate and guard their valuable irrigated crops.

The design and construction of a bandhárá should be similar to those of an intake weir (Art. 133).

107. Reports, Plans, Estimates, and Specifications.

The office work in connection with the preparation of projects for these small works should necessarily be on a much less elaborate scale than what is required for important large schemes. For the reconnaissance report it is advisable to draw up a printed form giving the details of which particulars are required, so that the latter may be entered shortly against the items specified. The forwarding report should also preferably be in statistical form. From this it can be seen whether the tank has sufficient storage for the area already irrigable, and if it is practicable to increase that area. The plans should be limited to a plan and longitudinal and type cross-sections of the dam or bandhárá (with detailed cross-sections roughly drawn in pamphlet form for tank projects to arrive at the quantities), and to plans and cross-sections of the waste weir and outlets. A small index plan to locate the work is desirable. The estimates should be in the usual detailed form, and short specifications should be drawn up for the district generally and printed.

CHAPTER IX.

CANALS IN GENERAL.

108. Calculation of Full-Supply Discharge.

AFTER the alignment of a canal has been settled, the calculation of the full-supply discharge of its different portions has to be made in order to determine their sectional areas. Where the total amount of supply available is a fixed quantity, as from a reservoir, the discharge of the head of the canal and the extent of the total irrigable area have to be limited correspondingly. Where there is an unlimited amount of supply available, as from a large river, the extent of the area irrigable will be the controlling factor in the calculations. This area will depend upon the proposed scope of the work, and this again on the nature of the irrigable tract, the number of the agricultural population, the character of the markets, and the amount of manure procurable, etc.

In either case the amount of the full-supply discharge of the canal has to be worked out by applying the duty of water (Art. 21) to be attained to the area to be irrigated, and allowing for loss in transit (Art. 19). The calculation for the discharges of the different sections has to be made, working from the tail upstream (Art. 19 (*c*)). In this respect it is generally necessary to consider only the conditions in the monsoon season, as then the irrigated area will be at a maximum, and among the crops will be those requiring much water, such as rice, while a considerable amount of evaporation will take place. These demands have to be provided for during breaks of the monsoon, over which the canal must be able to tide. In the cold weather the crops then matured require comparatively little water, and evaporation is small in amount. In the hot weather the area of the crops—perennial and seasonal—will generally be relatively inconsiderable.

Care should be observed not to over estimate the supply available for the canal. It is best to take the average minimum into account, and to allow a little extra beyond this. Thus during bad years the canal will irrigate with the then enforced high duties a fair proportion of the usually irrigated area, and in good years will meet the demands of the whole of that area.

109. Expansion of Canals.

(*a*) *Masonry Works.*—If a canal is successful, the area under irrigation will tend to expand to its limit, and the amount of its expansion is often a measure of the success of the work. The time may therefore arrive when it will become necessary to enlarge the canal and its subsidiary works. This time should be foreseen when the project is originally under construction, and the scheme should therefore be so designed and executed that the cost of its enlargement will not be greatly increased by having to pull down much work. As there is difficulty in securing water-tight connection between new masonry and old earthwork, it is desirable that masonry works should be designed at first, so as to be able to serve without extensive remodelling or alteration for areas somewhat greater than those of the initial scheme. Thus the sills of head regulator sluices and beds of aqueducts should be built a little lower than is required for that scheme so that they will suit a slightly deeper canal. The wing walls of cross-drainages are frequently a large and expensive part of the whole structures. Where this is the case, the works should be constructed so that they may be widened somewhat without altering the wing walls.

A small increase of the irrigation waterway of cross-drainage works beyond normal requirements is desirable also to meet abnormal ones, such as after a prolonged closure or period of low water, when more than the designed full-supply discharge has to be passed down the canal. This extra discharge could not be arranged for were the capacity of the cross-drainage works limited to that only sufficient for the calculated full-supply.

(*b*) *Earthworks.*—Where the canal is in cutting, the spoil side banks should be set back a little so that the excavation may hereafter be widened without moving them. In fact, it may often be desirable to anticipate expansion conversely by reducing originally the width of the excavation to what is required during the first few years of irrigation, and then gradually to work up to the originally designed full width as the growth of irrigation proceeds. Thus the capital expenditure, and therefore the interest charges, will keep pace with that growth, and will not be unduly in advance of it. Where, however, the canal is in embankment it would be wrong thus to reduce the designed width initially, as made earthwork should improve with age, and therefore, if practicable, it should not be disturbed. On the contrary, if the bed is only a little above ground level, it may be justifiable in the first construction to set back the side banks a little outside the designed section to provide for future expansion, as the excess cost of this will be but small.

110. Revenue Management.

Although the progress of irrigation depends mainly upon the initiative of the irrigator, and is influenced greatly by weather and market conditions, still it is affected by the nature of the revenue management of the work. The first thing the irrigator wants is an assured supply of water, and thereafter as few restrictions and as little interference as possible. Supply must therefore be carefully regulated so as to suit all legitimate requirements. Restrictions on the individual irrigator should be clearly in the interest of the general body of cultivators, who will thus be convinced that the orders are not of a penal or vexatious nature. Interference or extortion by the lower-paid members of the staff should be minimised by a proper and notified system of rotations (Art. 23 (*b*)), and all petty tyranny should be put down with a firm hand. When closures or other general measures affecting the canal as a whole are necessary, they should be carried out after consultation with the irrigators to suit their convenience as far as practicable, and due notice thereof should be given to them. For instance, every advantage should be taken of heavy rainfall to close the canal in order to effect repairs, weed clearances, etc., as then water will not be required for the crops.

111. Maintenance.

Maintenance has for its object the preservation of the works in the best state, first, for structural security, and second, for the proper passage of the supply. In regard to the former, the bulk of the repairs should be executed during a comparatively short period, when it can most conveniently be done, so as to concentrate labour and to limit the amount of supervision. Work in connection with the latter should proceed continuously, for a canal out of correct regime will suffer much loss of water in transit (Art. 19), or, if damaged, will tend further to injure itself. Thus maintenance has to be carried out partly by a permanent staff and partly by repair gangs. This is indicated by the term "maintenance and repairs"—usually adopted in Indian estimates.

Maintenance proper consists chiefly in the regulation of water into and out of the canal (Art. 23 (*b*)); petty canal repairs and clearances; inspection path repairs, etc.; plantation work; and in patrolling the works to prevent leakage, waste, and trespass. Repairs include large canal restorations and extensive clearances of silt and weeds. When practicable, it is important that minor improvements, such as flattening curves, removing longitudinal irregularities, raising low banks, etc., should be gradually carried out, so that the works may be continually bettered as experience proves to be necessary. The principal current repairs are detailed below. It is essential that they should be thoroughly and neatly done:

(i) Repairs to the headworks, including flood embankments.
(ii) Maintenance of banks to full height and section, especially near masonry works.
(iii) Filling rain scores down the slopes.
(iv) Filling cracks and rat-holes, etc., in banks.
(v) Rooting out shrubs and coarse vegetation.
(vi) Attending to drainage where necessary.
(vii) Maintenance of section of canal waterway and removal of silt and obstructions.
(viii) Maintenance, similarly, of the stream waterway near cross-drainage works.
(ix) Staunching of leaking sections of the canal.
(x) Repairs to masonry works, especially with regard to their foundations and to leakage.
(xi) Repairs to sluices, ironwork and woodwork (which should be kept well painted or tarred)..
(xii) Maintenance of benchmarks, mileage marks, high-flood marks, gauging stations, inspection path, rest-houses, plantations, etc.

The works should be put into thorough order before the monsoon, and should be inspected soon after its close with a view to repairing early any damage which may then have been sustained. During the monsoon it may be necessary to strengthen the patrol guards so that the increased staff may suffice to carry out immediately all ordinary repairs then necessitated. When not required for this primary duty, the men should be employed in effecting improvements.

112. History of Canals.

In order to assist the management of an important canal or other irrigation work, it is desirable that a history of it should be maintained. This should give a general description of the main features of the project, its history, year by year, and proposals for its improvement or extension. An account of its construction should be written, and all special difficulties met with, or points of interest, should be noticed. A similar account of each year's constructive work, including extensive repairs, should be added. There should also be a revenue history of the work posted up annually to record how the irrigation progressed ; the character and effect on the irrigation of the seasons and the supply available ; the nature of the crops grown and the reasons influencing their selection ; the progress of the revenue and the causes affecting it ; and other points of interest. Accompanying this should be a series of tabular statements, such as a list of the subsidiary works, with details of their principal dimensions ; rainfall and discharge tables ; tables of areas, out-turn, and value of crops irrigated ; tables of gross revenue, working expenses, and net revenue, etc. Where practicable, these tables should be illustrated by diagrams. The history should have an index map on a scale sufficiently large to show all important sections of the project and developments of it which may take place from time to time.

One of the most important items noted above is the account of proposals for improving or extending the project. This should note the reasons for bringing forward the suggestions or for rejecting them, or postponing the execution of the works contemplated. It sometimes occurs that years after a subsidiary scheme has been negatived for good cause, it is once more recommended by those who are in ignorance of its previous history. The record noted above would obviate this waste of time and energy, and might also lead to the prosecution to completion of good schemes previously put aside and otherwise forgotten.

113. Alignment.

(*a*) *General Considerations.*—When a canal starts from a reservoir the alignment of its head is governed by the best situation for the outlet from the storage which is the ruling factor. When, however, it is led from a weir, many considerations have to be taken into account, such as: the best site for the weir in respect to its foundations, cost, discharging capacity, and extent of backwater (Art. 132); the avoidance of crossing many large tributary streams, especially near their confluence with the main one, which will block their discharge in high floods; the avoidance of an expensive head section before irrigable command is obtained, due either to hard formations, deep cutting, or a great length to be traversed; the avoidance lower down of rolling country, which will involve a tortuous course and numerous cross-drainages, or of high land which will diminish the area irrigable, and necessitate the increase of the length of the canal to obtain sufficient command. All these points must be studied carefully and the generally best project evolved.

The proper location of the crossings of drainage lines is most important for the correct alignment of the canal, as the cost of the cross-drainage works on them is often a heavy item of the total expenditure. A crossing should be selected, when practicable, where the waterway is sufficient and the catchment at a minimum; the canal approaches are high, and the formation sound; the foundations are good; materials for construction are available; and the approach and exit of the stream are straight and the cross-section regular. Sufficient survey, including enough cross-sections and trial pits, of alternative alignments should be made and the best line selected.

(*b*) *Canal Alignment.*—Usually the alignment for a canal which is cheapest in original cost is on a ground contour falling at the rate of its longitudinal slope. This, however, will make its length a maximum one, to which the objections are:

(i) The cost of maintenance will be increased;
(ii) The time the water takes to reach the irrigated land will be lengthened;
(iii) The loss of water in transit will be greater;
(iv) There will be a loss of command due to the larger total fall of the canal.

It is better, therefore, to shorten the length of a canal by substituting diversions for the more sinuous parts of the falling contour than to follow too closely the irregularities of the country. The best alignment is thus one which consists of long, straight lengths, connected by short, regular curves, so as to avoid great differences of ground level. In the case of large canals in soft alluvial soil, it has been found difficult to maintain very long, straight reaches, owing to the oscillation of the water, but this has no practical effect on small canals in soil of ordinary hardness.

Wherever practicable, the canal and its main branches should be aligned to get on to the watershed as soon as possible, and thereafter to remain on it so as to obviate the necessity for cross-drainage works and so as to command land on both sides. The alignment should avoid difficult country, i.e. that having an irregular surface owing to ridges, depressions, and watercourses, or consisting of rocky, sandy, alkaline, or waterlogged strata. Good water-tight formations which can be cheaply excavated should be preferred. The more the cross-section balances excavation and embankment, the cheaper will be the canal, for it is generally not economical to effect such equalisation in the longitudinal section as the lead for depositing spoil in thus increased. To determine the nature of the subsoil, trial pits should be dug along the centre line at convenient intervals, and especially where the material changes, and at the sites of cross-drainage works (Art. 59 (*d*) (iii)). The more numerous, in reason, these pits are, the more exact will be the information they will give. Their cost will be small compared with that of the mistakes in under-estimation they will prevent.

(*c*) *Setting Out.*—The centre line of the canal should be set out by stout pegs driven in at intervals of, say, 100 feet, and should then be lock-spitted. From this centre line other lines should be lock-spitted to indicate the bottom and top widths of the excavation and the centre lines and toes of the embankments. During the survey and construction of the canal, permanent benchmarks should be made as frequently as possible.

114. Curves.

The objection to a very sharp curve is that at it the water flows irregularly, tending to leave the convex, or inner, and to erode the concave, or outer, side, and to deposit silt unsymmetrically across the section of the canal which will increase the destructive action due to the curve. This effect is much more pronounced in canals in alluvial or soft soil than in those in hard material.

The minimum radius measured from the centre line of the canal should usually not be less than—

For large canals, 15 times the bed width ;
For small canals (under 25 cusecs), 10 times the bed width.

Better radii to adopt generally should be, for non-alluvial canals about twice, and for alluvial canals about thrice, what has been stated above. The greater the radius, the better is the curve for maintaining regular flow, but long curves increase the difficulty of setting out and constructing the canal. When a canal is fenced by wire, a straining post is required at the end of each chord of a curve, and this is a minor objection to sharp curves. On the very large canals of Northern India the curves usually adopted vary from 5,000 to 15,000 feet in radius.

An important canal should have its curves set out by means of an instrument ; a small canal can have its curves marked with sufficient accuracy with a tape.

115. Velocity.

(*a*) *The Canal.*—The velocity of the water in a canal has to be regulated so that it will not scour or erode the soil through which it passes, but should otherwise be as high as practicable so as to avoid silting. It is better to have a somewhat too high than too low a velocity, as it is easier to deal with scour and erosion (by falls or by pitching, etc.) than with silting. The maximum mean velocities in feet per second allowable generally in different soils are :

Light sand	1·5 to 2·0
Sandy loam	2·5
Soft clay	3·0
Hard clay or grit	4·0
Soft rock	5·0 to 8·0
Hard rock	8·0 to 12·0

The bottom velocities permissible, which are those which actually affect the bed, may be taken as about four-fifths of the mean velocities. (See also Art. 36.) In Northern India the minimum mean velocity required to prevent silting and the growth of weeds is taken as 1½ feet per second, and the general maximum mean velocity to avoid scour, etc., of the alluvial soil at about 2¾ feet per second. The silting of the bed and sides may alter the nature of the wetted perimeter of the canal. The bed will remain free from weeds, but the sides may become covered and protected by their growth.

The smaller a channel, the greater may be the calculated velocity of flow, as this will be reduced by the state of the sides, and because the erosive power of water varies directly with its volume. The extra velocity thus permissible will, however, be considerable only in the case of small channels.

Not only erosion and scour, but also silting have to be prevented by the velocity allowed. A canal is maintained in good regime when it does not erode, scour, or silt. Silting takes place most abundantly in alluvial canals (Art. 202 (*b*)), and varies with the coarseness of the silt carried. Generally, a velocity of from 2 feet to 3 feet a second is required to reduce the amount of deposit by carrying the silt on to the fields; there the lighter, soluble, clayey variety has a manurial value, but the heavier, insoluble, sandy kind is useful only in rendering heavy clay soils lighter and more porous if it is worked into them.

(*b*) *Cross-Drainage Works.*—At cross-drainage works, particularly long aqueducts, the velocity should be increased so as to diminish the area of the canal waterway at them. To create and maintain this greater velocity, the general longitudinal slope of the canal will have to be steepened, both upstream and downstream of the cross-drainages, for certain distances, which may be taken at about twenty times upstream and ten times downstream the increase in velocity. Thus, if that increase is from 2 feet to 5 feet per second, the slope of the canal should be increased upstream of the work for a length of, say, (3×20=) 60 feet, and downstream of it, for one of (3×10=) 30 feet.

A considerable increase of the velocity of the water in the canal approach to and exit from the cross-drainage work will necessitate the pitching of the waterway of the length of the canal affected, if it is in embankment, as will usually be the case. That length will be the distance from the point where the velocity commences to increase beyond 3 feet per second to that where it has decreased to that rate. The cost of this pitching should be compared with the saving resulting from the contraction of the canal waterway at the cross-drainage. If the former exceeds one-half of the latter, the diminution of the section of the cross-drainage work to produce an eroding velocity may be foregone, as that entails a certain amount of risk to the embankments. For each work in each section of a canal the quantity of pitching is nearly constant, but the saving by reducing its cross-section will vary directly with its length between the abutments.

116. Longitudinal Slope.

(*a*) *General Remarks.*—The velocity of the water in the canal depends upon its cross-section and its longitudinal slope. That slope should be adjusted so that the velocity should be as great as is practicable without causing erosion of the sides or scour of the bed of the canal and great loss of command.

The advantages of a high velocity are:

(i) It reduces the area of the cross-section, and thus the cost of the canal;
(ii) It retards the growth of weeds;
(iii) It lessens the deposit of silt in the canal;
(iv) It diminishes the time of transit of the water, and thus the loss which occurs during it.

The disadvantages of a high velocity are:

(v) It increases the cost of maintenance if it tends to cause erosion or scour;
(vi) It lessens the command ,by the greater longitudinal slope which has to be given to the canal, and may prevent the irrigation of high land by flow. To avoid this, a decreased longitudinal slope may have to be given for certain sections of the canal.

It is advisable to maintain an approximately constant velocity throughout the length of the canal, so that the silt suspended in it may be carried to its tail or on to the fields. To enable this to be done with a discharge diminishing from the head to the tail, the canal should be divided into sections, in each of which the discharge is practically the same throughout. The longitudinal slope of each section will thus nearly be proportional inversely to its hydraulic mean radius. In channels of similar section the velocity increases with the depth. Taking the canal as a whole, its longitudinal slope will therefore increase from the head to the tail. (See also Art. 233, end of (*c*)). As the slope of the country usually decreases downstream, a long canal may thus tend at its end to return to the river, and there are a few instances of this effect of the opposed slopes where the land is very flat. If this result will take place, it may be necessary to elevate the canal head either by increasing the height of the headworks, or by placing them further upstream.

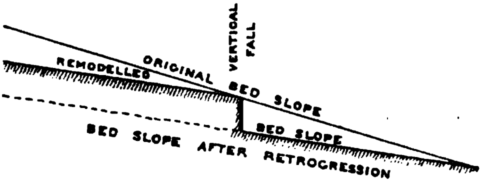
In order that the designed longitudinal slope may be maintained, bed stones should be securely fixed with their tops at true bed level in the centre of the canal opposite each furlong stone. If they have to be spaced more closely, indicator stones should be placed on the canal bank opposite the intermediate bed stones. The silt clearance of the canal should be carried out with reference to the level of its bed stones.

(*b*) *Retrogression of Levels.*—If the longitudinal slope is too flat, silting will take place. If, however, it is too steep, scour will occur, and what is known as "retrogression of levels" will be produced by the water cutting down and back the bed of the canal to a slope giving a velocity which the soil will stand (Fig. 51A). The scouring of the bed will cause the lowering of the surface of the water, and will thus reduce the discharges of the distributaries taking off from the canal, which were designed to be given with its levels as constructed. Further, as the scour is not likely to be uniform, and the detritus will be deposited irregularly downstream, the regime of the canal will be injured. Silting, by raising the bed and water surface, will, on the contrary, increase the discharge of the distributaries; it will also affect the regime of the canal,

FIG. 51A

RETROGRESSION OF LEVELS

LONGITUDINAL SECTION OF CANAL



and tend to endanger the embankments. Of the two defects, silting is the worse, as it can be remedied only by constant removal or attention, entailing recurrent expenditure. Scour can be dealt with once for all by constructing vertical falls at suitable intervals, and thus re-grading the canal as shown in the Figure.

117. Side Slopes.

The following are minimum side slopes generally adopted for different soils, depths and heights :—

A. In Excavation.

	Up to 8 Feet in Depth.	From 8 Feet to 15 Feet above Bottom.
Light sand	2 or 3 to 1	3 or 4 to 1
Sandy loam	1½ to 1	2 to 1
Soft clay	1 to 1	1½ to 1
Hard clay or grit	½ to ¾ to 1	¾ to 1 to 1
Soft rock	¼ to 1	¼ to ½ to 1
Hard rock	⅛ to 1	⅛ to ¼ to 1

B. In Embankment.

	Up to 8 Feet in Height.	From 8 Feet to 15 Feet below Top.
Inner, water slope	1½ to 1	2 to 1
Outer, land slope	1 to 1	1½ to 1

In the case of excavation, the side slopes have to be made flatter for soils which have a small resistance to slipping than for those which have a great one. No ordinary side slope may prevent an excavation in quicksand from caving in, and it may be necessary to pitch the sides, or even build retaining walls, to make those secure in such a formation. The effect on the behaviour of the soil by the wetting of the canal must, of course, be taken into account.

In order to prevent slips, a flatter slope is required for the side of an embankment which is under water than for that of one which is in the dry; also, for a high embankment than for a low one.

Theoretically, the side slopes, both in excavation and in embankment, may be made steeper above canal full-supply level than they are below it, and the former flatter at the top, and the latter flatter at the base, when the height is considerable, so as to allow for surcharge. Practically, this is not usually done, and the flatter slopes are continued throughout as the resulting saving for ordinary heights is not great, and the excess cost of omitting it is justified by the increased safety secured for the wetted lower parts by the reduction of the surcharge on them.

It is found that the side slopes of cuttings generally silt up to ½ to 1 in alluvial canals, which is therefore the side slope to be taken into account in calculating the discharging capacity of the canal, and not the one actually constructed. The silt thus deposited should not be cut away during clearances, as it lessens the percolation and absorption from the canal, and if removed is likely to be replaced quickly by further deposit.

118. Cross-Section—Depth and Bottom-Width.

The area of the cross-section of a canal depends upon its depth, bottom-width, and side slopes. The last named are governed by the nature of the materials passed through, the two first named bear a relation to each other. Theoretically, the discharge of a regular trapezoidal channel is at its maximum when its hydraulic mean depth is half of its central depth (Fig. 57, p. 270). This is the section with the smallest wetted perimeter in proportion to its area, and it thus retards flow the least. In it a semicircle struck from the water surface will touch the side slopes and bed, which will thus all be tangential to it. It is the best section for very small channels in even ground, or with a gentle cross fall, but for large ones is not likely to be the most economical nor even practicable for them, as it generally makes the depth bear an undue proportion to the bottom-width. In large canals such a section tends to increase the amount of silt deposit and the rate of the cost of its removal, and also the loss in transit which depends greatly upon the pressure head causing absorption.

If the canal is too deep, it may lead to excavation in hard soils or rock, and thus increase the cost. If it is too shallow, it may cause reduction in the velocity of the water, and hence an increase of the cross-section and of its cost. Shallowness in a channel is, however, advantageous when it has to supply intermittently numerous minor channels, as then fluctuations in its discharge will not affect its surface level proportionately.

It is also of importance in alluvial canals in order to lessen silting (Art. 203 (*d*)). The smaller the cross-sectional area of the canal, other things being equal, the less will be its cost. The determination of the proper relation of the cross-section to the longitudinal slope of the canal therefore requires the exercise of judgment.

In regard to the loss in transit, the minimum percentage of absorption in canals with side slopes of ½ to 1 will be given when the ratio of the bed-width to the depth is intermediate between 1·236 and 2·472, or, say, is equal to 2. When this ratio cannot be adopted, the bed-width should not be made less than twice the depth. This consideration is, of course, of most importance in porous formations.

In side-long ground the greater the proportion of the depth to the width of the canal, the less will be the amount of excavation. This ground formation will, as a rule, be met with only in non-alluvial canals. For such canals of fair size a rule which has been proposed is to make the bottom width in feet equal to the square of the depth in feet, *plus* one.

In America certain canals have been deepened with a "sub-grade" of from 1 to 3 feet in the centre beyond the true bed level so as to induce a central current, but the friction of the sides will naturally have this effect. Others have there been deepened on the hill-side so as to make the current hug the natural hard ground, but a canal by silting and scouring will make its own working section in time. Both these refinements therefore seem unnecessary.

119. Full-Supply Level.

When a non-alluvial canal is in excavation, its full-supply level should be kept as a rule about 6 inches below ground surface in the case of small channels, and about 1 foot below it in that of large canals, so as to lessen the chance of breaching. The country traversed by such canals will generally slope at a fair inclination, so that the loss of command entailed by thus lowering the canal full-supply level will not be great. In alluvial canals where the land slopes are very flat, the full-supply level is usually designed to be about a foot above the ground surface, so as to obviate loss of command, and not more than 2 feet above it so as not to endanger the banks.

When a canal is in embankment, its full-supply level should be from 2 feet to 3 feet below the top of the side banks in the case of small canals, and from 3 feet to 4 feet below it in that of large ones. Embankments are liable to crack for some depth below their tops by the drying action of the sun and wind, and therefore water should not be allowed to rise too high against them. Moreover, by raising the embankment the earthwork in it at and below canal full-supply level will not only be wider, but will be more compressed, and on both these accounts will be more water-tight. The free-board thus given to the embankments provides a margin of safety in case the earthwork should settle, or the canal surface rise to an abnormal height.

In respect to masonry works on the canal, as the water can rise to the top without finding a passage through them, such an extent of free-board is unnecessary, and may he reduced to less than one-half that allowed for embankments. The actual junction of the masonry with the earthwork must, however, be stepped up somewhat so as to prevent a leak forming between the two.

120. Adjusting Depth and Bed Levels.

(*a*) *Depth.*—As the full-supply discharge of a canal decreases from the head to the tail, not only will its bed-width have to be diminished, but also its depth may have to be lessened so as to give it a proper cross-section throughout its course. If there are works across the canal, such as falls or rapids, the decrease in depth can there be made at once. Also, if the lessening of the discharge is due to the take-off of a large branch from the main canal, the depth of the latter can be reduced just downstream of the former. Where, however, the full supply of the main canal diminishes regularly by the draw-off from it of several minor channels, its greater depth upstream should gradually be decreased to its smaller depth downstream by flattening its longitudinal bed slope for the required distance. This will avoid the formation of a vertical step up in its bed which would cause an abrupt change of section, and might lead to silting and a retardation of flow upstream. It will also allow the channel to drain during closures, which it would not do if its bed were made level for a reduced distance, and still less if it were abruptly stepped up (See also Art. 233, end of (*d*).)

(*b*) *Bed Levels.*—It occasionally becomes necessary to remodel a canal, and for this purpose to re-adjust its bed levels. The fixed points which have to be worked to, or modified as far as practicable without extensive alterations, are the bed levels of masonry works across the canal, or forming sections of it. It is for this reason advisable in the original construction of such works to make their beds somewhat lower than required by the then design, so as to give scope for possible future adjustments (Art. 109 (*a*)). Having settled the final bed levels of the masonry works as remodelled, those of the intermediate canal earthworks are then altered to suit.

121. Excavation of the Canal.

If the full irrigating capacity is likely to be acquired soon, it is advisable to excavate a moderate-sized canal 6 inches, and a fair-sized canal 1 foot, wider than the width calculated as sufficient for passing the discharge. This will allow for the retardation of the velocity due to the roughness of the excavated sides, or to the growth of weeds and aquatic plants, and for the diminution of the section due to silting. The cost of thus slightly increasing the width of a canal is much less than the capitalised cost of frequent small clearances to restore the designed section, while the entire removal of silt prevents the canal from waterproofing itself properly. Moreover, a small extra bed-width will provide for an increase of the ordinary discharge when this becomes necessary, owing to an abnormal demand for water, such as will occur after a long closure or period of low water. It is cheaper to widen the canal a little during its construction than to do so after it is in operation, when an increase of its sectional area is necessitated by the larger demands of irrigation.

If the ground is not hard, the surface can be most cheaply excavated by first ploughing it up, and after that has been removed, lower layers can similarly be loosened. The upper part of the soil thus treated can be dragged by scrapers to form the side banks. In countries where labour is dear and skilled labour is available, patent excavators have been used successfully. In the tropics, where the conditions are the opposite, such machines have not been found economical.

It will generally be best to excavate the canal at first in steps with vertical sides, and then to dress off the projections to the finished slope. It is not worth going to much expense in this dressing, and particularly is it not advisable to attempt to dress hard soils and rock to the exact calculated section. A little widening of the section will be cheaper and more practicable to execute, and will increase the discharge more effectually. Projections of large size, and especially into the calculated section, should, anyhow, not be allowed.

A canal in excavation should not be led too close to the edge of low-lying ground, for if this is done leaks or breaches may be induced. The minimum distance which should be preserved depends upon the nature of the soil. If that is solid and compact, at least 10 feet (or twice the full-supply depth if that is greater) from the outer toe of the downstream embankment should suffice for it; but if the ground is fissured or porous, the minimum distance should not be less than 20 feet, or four times the full-supply depth of the canal if that is greater. The cheapest section in ordinary soil is one in which the excavation and embankment balance each other. This may also avoid the necessity for taking the canal into hard soil or rock, which will add to the expense of construction.

122. Utilisation of Canal Spoil.

The spoil derived from the excavation should first be disposed of to form the two side banks to their minimum height and section if the canal is double-banked, or the downstream bank if it is single-banked. If more spoil is available than is required for this extent of construction, the extra material should first be utilised in increasing to a certain extent the section of the downstream bank and the balance thereafter for strengthening (or, in the case of a single-banked canal, forming) the upstream bank, and so on. It is advisable to utilise the extra spoil in widening the banks rather than in heightening them greatly. Of course, the banks should be constructed from the beginning to their final section, which should be set out with reference to the calculated quantity of spoil available, and if this is in excess, that should for the sake of appearance be neatly formed and not thrown up in unsightly heaps.

Where the ground level exceeds the full-supply surface of the canal by 2 feet or more, it is not necessary for safety to form a downstream bank, but it is better to make one there to preserve the continuity of the line of embankment. Where, however, the ground is hard at 1 foot above, or at a slightly higher level, or also a little below canal full-supply, and where damage will not be caused by water flowing over it or lower lands, natural escapes (Art. 148) can be formed on the downstream side for the discharge of excess supply in the canal.

123. Berms.

Where a canal is in excavation, berms, or strips of natural ground, should be left between the inner toe of the bank and the edge of the excavation (Figs. 57 and 58, p. 270); these will allow of the future widening of the canal, if that becomes necessary, without removing the banks. Moreover, should the side slope of the excavation, or that of the spoil, have originally been made too steep to stand, the berm will permit of a slip occurring without undermining the bank and causing it to block the canal. For this reason the width of the berm should have some reference to the side slopes, and the following dimensions are therefore recommended for it in good soils:

Minimum width—2 feet, *plus* quarter the width of the combined side slopes of excavation and bank;
Maximum width—2 feet, *plus* half the width of those combined side slopes.

Other considerations fixing the width, which are of special importance in porous soils and alluvial canals, are that it should be sufficient to prevent the ground underlying the spoil bank from becoming sodden and unable to support the bank, and to allow space for the deposit of silt to staunch the canal (Art. 233 (*g*)). Lastly, the berm on the downstream side should be wide enough to carry the inspection path (Art. 126). The alignment of the canal bank, in order to look well, should be kept regular for long lengths, and the width of the berm should be adjusted accordingly to average conditions.

When the surface of a berm is somewhat below the level of the canal full-supply level, weeds and rushes may grow on it, which will retard the velocity of the flow. In course of time, however, such places will generally silt up to canal full-supply level, and then the growth on the berms will no longer be objectionable in this respect.

When a berm is a wide one and the canal excavation is in soft soil, the amount of run-off from rainfall on the former will gutter the slope of the latter if allowed to pass naturally over it. In such a case the surface of the berm should be made with a slight slope away from the canal, and a drain should be formed along the inner toe of the canal bank, and should be discharged at intervals through that bank or down the excavation slope in paved gutters.

Where a canal is in embankment, the formation of berms would add considerably to the cross-section of the bank, and thus to the cost of construction, and the additional capital expenditure would not yield any return until the canal was widened. It is therefore not the practice to construct berms in embankments, but, when the widening of the canal becomes necessary, to set back the side banks by removing the earthwork of their inner slopes and adding it to their outer ones. If, however, an increased width is likely to be required in the near future, it is better practice to allow for it originally by setting back the side banks. Where a canal is in excavation and the berms are submerged, the waterway is increased, but the bed-width is not diminished on this account, as the velocity of flow over the berms is slower than that of the central part of the canal, and the berms are likely to silt up.

124. Borrow Pits.

The borrow pits, from which the material for the embankment is obtained, should not be nearer the toe of the slope than twice the height of the bank measured from that toe. Next the bank they should not exceed 3 feet in depth, and should not be deepened therefrom at a greater inclination than 1 in 10. Wherever economically practicable, and certainly where the ground has a steep sidelong slope, or is porous, and in the case of alluvial canals, the borrow pits should be confined to the upstream side of the upstream bank, so as not to induce leakage from the canal on the downstream side, which might cause a breach, as the pits virtually increase the water-pressure head. They should not be excavated in long continuous lines, as, if they were, they might lead to the formation of a scour channel close to the embankment, which might eventually erode or undermine it. To obviate this the pits should be separated from each other at intervals of, say, 200 feet by strips of unexcavated ground wide enough to prevent breaching.

An objection to borrow pits is that in them water may collect, stagnate, and form the breeding-ground for mosquitoes, which will carry malaria in the neighbourhood. This objection has not much force in the open country, through which most of the length of the canal will lie, and may be met where the line passes near a village by draining the pits by narrow cuts through the separating strips if the ground is hard, or by pipes laid through the base of these where the soil is soft. Field drainage should also be admitted into them to silt them up.

125. Drainage of Swamps.

If the canal crosses swamps, it is advisable to drain them by channels leading to natural drainage lines. If the canal is in embankment, the drain, if parallel thereto, should be cut outside the borrow pits, and these should be drained independently into it. If it is in excavation, the canal itself may act as a drain but if its full-supply level does not permit of this, drains should be cut not less than 20 feet from the canal.

Frequently swamps are due to barriers of impervious material blocking their natural outlets; in such cases it may suffice to cut through these barriers so as to give the water a clear outfall.

The general drainage of the canal system as a whole has been discussed in Article 16.

126. The Inspection Path—Milestones, etc.—Canal Plantation.

An inspection path should always be provided so as to permit of the rapid and easy inspection of the canal. It should be situated on its downstream side (as that is the side where breaches would be most dangerous), and a few feet from the edge of the canal, where the ground is above full-supply level, so that the waterway may readily be inspected. As a rule, the path should not be formed on top of the canal bank (except where the ground is below full-supply level), for if carried thereon the traffic on it would tend to wear the bank down.

For ordinary canals the path need be only 4 feet wide to permit of riding or walking; for important ones a roadway 10 feet wide may be necessary for driving purposes. It should be set out in neat lines and curves, parallel to the canal, and should be levelled and cleared of ant-heaps, rat-holes, bushes, rank vegetation, overhead branches lower than 10 feet, etc., but, except in important parts, or where the ground is wet, need not be surfaced, as the traffic on it will be small. Where the canal crosses a drainage line the path should be carried over the canal bank with a sloping alignment, and across the watercourse clear of and parallel to the cross-drainage work with longitudinal slopes of about 1 in 10. The bed of the stream should be drained, and the crossing, if necessary, made hard by flat pavement, which should be continued up the approach slopes to at least 1 foot above high-flood level.

On the side opposite to the inspection path mile and furlong stones should be fixed, and should have their mileage marked (preferably engraved) on them, with the number of the back mile as numerator and that of the back furlong as denominator, so that they may be legible from the path, and each stone may indicate the complete mileage. The mile stones should be larger than the furlong stones, should be securely founded and fixed, and should be utilised as benchmarks, for which purpose their levels should be cut on them. (See Art. 308.)

It will add greatly to the appearance of a canal of any importance, and to comfort during its inspection, if trees are planted along it. The trees selected for planting should be ones affording fruit or other saleable produce, so that they will be a source of revenue, and need not be cut down to realise profit. Besides affording shade, they will act as windbreaks to crops to their leeward. Although they protect the canal from direct evaporation, they probably induce a greater amount of indirect evaporation from their leaves. (See Art. 47.)

127. Provision for Cross Traffic.

As a canal offers a great barrier to traffic, means of crossing it should be provided at convenient intervals. Where the full-supply depth of the canal exceeds 3 feet, or where the cross traffic is considerable, bridges will be necessary. For made roads substantial bridges of full width are, of course, required, but as these works are costly, even on small canals, they cannot be erected at short intervals. On such canals it will be enough at intermediate distances to construct cheap cultivators' bridges, or even footbridges, sufficient for the passage of field implements and cattle. On large canals even these become too costly, and they thus separate the inhabitants on the two banks nearly as effectually as a river. On them ferries are occasionally established to give communication. Iron bridges are expensive and difficult to maintain, especially in out-of-the-way localities.

To reduce the cost of bridges the canal waterway is sometimes diminished through them. Such restriction should never exceed 30 per cent., so as not to interfere unduly with the velocity of the water. When a canal will probably be enlarged in the near future its bridges should be built of full waterway.

To increase the number of crossings every advantage should be taken of cross-drainage works, under or through which, when sufficient headway can be arranged, roadways should be led with proper approaches up and down the banks of the streams.

For canals of less depth than 3 feet, and where there is but little traffic, level crossings should suffice. The approaches and crossings should not be less than 10 feet wide, and the former should be neatly sloped down to the canal bed on each side, with gradients of not less than 1 in 10. Such crossings should be made, if practicable, where the full-supply level is at least 1 foot below ground level, so that the canal will not be liable to be breached by the wear and tear of the traffic. If, however, this is not feasible, the approaches should be led over paved ramps, carried at least 2 feet above canal full-supply level.

Crossings should, whenever possible, be made where the soil is hard enough to resist traffic. When, however, the ground is soft, the slopes of the approaches and the canal bed should be protected by flat drystone paving continued at least to 1 foot above full-supply level.

Where crossings are far apart, or do not exist, it will be a convenience to provide drinking places for the watering of the cultivators and their cattle ; this will also save the canal from injury by trespass along its course. All that is necessary for this purpose is to make approaches down to the canal with gentle slopes, which should be paved if the ground is soft.

128. Land Acquisition and Demarcation.

The land to be acquired for a canal should provide for the canal proper, including its berms, inspection path, and embankments, and for borrow pits and subsidiary works. A proper land plan showing the limits of the canal property (which should be permanently demarcated by boundary stones or marks) should be made and carefully maintained up to date.

Where a canal is likely to be damaged by the passage of men or animals, the boundary line of its property should be hedged or fenced; but fenced crossings should be left at convenient intervals, i.e. at watering places, and when necessary gates erected across the inspection path, or otherwise trespassers are likely to injure the main fencing, etc. Hedges should be planted where drift soil or sand is liable to be blown into the canal, so as to prevent it from thus silting up the waterway. Hedges require constant attention in regard to blank spaces, which should be re-planted as soon as practicable, and they should, when necessary, be trimmed to stop their getting thin and weak.

CHAPTER X.

CANALS IN NON-ALLUVIAL SOILS—HEADWORKS AND EARTHWORKS.

129. Classes of Weirs.

THE different classes of weirs—storage (Art. 130), diversion or intake (Art. 131), pick-up (Art. 160 (*c*)), and waste weir (Art. 92)—have been defined in Article 2. In this chapter only two—storage and intake—will be discussed ; both of these are constructed across the main supply stream, and the canal led directly from the latter always, and also generally from the former. The first class is the more important and expensive of the two, and has to be located like a reservoir, where the conditions of storage are most favourable. The second class constitutes only the headworks of the canals, and has therefore to be situated with respect to the best general alignment for them (Art. 113 (*a*)) and the most fertile irrigable area which can be commanded. Both classes are similar in that river floods have to be passed over or through them.

130. Storage Weirs.

(*a*) *Storage Capacity.*—Owing to their size and purpose, these weirs have to be designed and constructed like masonry dams (Chap. VI), with additional arrangements for the safe discharge of flood water, whereas the latter works are generally restricted to storage requirements, and have subsidiary waste weirs for dealing with floods. The true storage weir impounds practically all the water behind it in the river channel, and thus does not submerge riparian land, which is usually of the most fertile description and most expensive to acquire. Such a weir should therefore be located where the river bed is wide and has a flat longitudinal slope, and where the river banks upstream are high. If in addition to the ordinary river channel there is a defined upper flood channel below weir-crest level, the storage capacity will be all the greater. The storage capacity will also be increased if the weir is situated just downstream of the junction with the river of a tributary having a large subsidiary basin.

(*b*) *Flood Depth—Temporary Crest.*—On account of the usually considerable height of the weir, it is not advisable that the depth of the flood over it should be great, partly to save the submergence of a large area of riparian land, but chiefly to avoid an excessive overfall on the foundations. To utilise for storage the volume occupied by floods, it is desirable to construct on the weir a temporary crest, having a height not less than the high-flood depth : the shutter arrangements of this would be kept open during floods to provide waterway for their escape, and would be closed after the end of the flood season to impound additional storage. The lower the flood depth is the less in height may be the shutters, and thus the cheaper will they be and the easier to manipulate. If, however, the total height of high-flood level above the river bed is small, the height of the temporary crest should be made greater than the rise of the flood, so as to impound storage sufficient to justify its construction. The bulk of the flood discharge would then take place over the low permanent crest, and not through the undersluices, and the flood waterway would be obstructed as little as possible by the weir. This will reduce silting up of the storage capacity, which will thus be chiefly due to the temporary crest and consist of impounded clear flow. It is, nevertheless, generally not advisable to make the permanent crest lower than, say, 2 feet above canal full-supply level; this will permit of the temporary crest being removed towards the end of the fair season, when the canal will be supplied by the balance storage and the then flow of the river. Silting is best avoided on rivers having a fair-weather flow fully sufficient to replenish the storage. Storm flows can thus be passed at once out of the reservoir basin, and only clear water will be impounded in it.

If trees are likely to be carried down in floods, the bays of the temporary crest should have spans of not less than 30 (preferably 40) feet, so that the trees may be carried through and may not be caught by them, for if they are, this may lead to the destruction of the weir by the consequent heading up of the river.

Where the overfall is considerable, the foundations will require the protection of a water cushion (Art. 32), as an apron (Art. 33) might not suffice to resist the pounding action of the water.

(*c*) *Undersluices.*—In order to assist the working of the temporary crest and to diminish the flood depth over the permanent crest and silting, there should generally be a large number of undersluices (Art. 35 (*b*)). Although the solid weir, even when pierced by undersluices, will obstruct the discharge of floods and thus cause silting, the greater the waterway through it, the less will be the height to which the floods will rise and deposit silt behind it. Where the sluices are numerous and their discharge great and prolonged, protection will be necessary for the foundations of the weir, and this can best be given by a water cushion (Art. 32). The sill of the sluices should be a little above the high-flood level of the water cushion, so as not to be submerged by it. If placed below that level, the effective head on the sluices will be reduced when they are thus submerged, and their discharging capacity will not be increased by a rise of the upstream high-flood level much beyond what it would be if their sills were raised just above tail high-flood level, while their cost and the difficulty of working them will become greater.

(*d*) *Weirs in Series.*—Storage in the river channel may also be effected by having a series of storage weirs at intervals along the course of the river from the most downstream of which alone a canal will be led. The ones upstream of this will simply be devoted to storage, and each can be formed by a low solid masonry weir on which will be constructed a high arcade of spans of, say, 30 feet width, which will be closed during the fair season by sets of horizontal shutters of, say, 5 or 6 feet height, one above the other. As the storage level falls below the bottom of each shutter, that shutter will be removed, and after all have been taken away, the arcade spans will be left clear and unobstructed until the close of the subsequent flood season, when storage will have again to be effected. These weirs should be constructed at suitable sites, and so that the full-supply storage level of a downstream one will, as a rule, not be higher than the permanent crest of the one upstream of it.

The arcades can be made to carry roadways or railways, and thus the weirs can be utilised both for irrigation and for communications, and their cost divided between these heads, to the financial advantage of each. Similarly, a roadway or a railway can, if desired, be led across a main storage or intake weir.

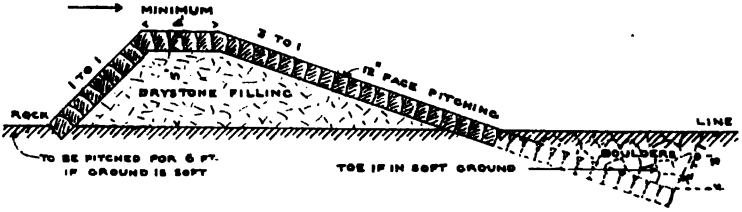
131. Forms of Intake Weirs.

The most rudimentary form of intake weir is one formed of brushwood laid across a stream and weighted with stone, and made staunch with sods and earth. This is, of course, a very temporary structure, which is liable to be washed away by each freshet, and such a weir is suitable only for a small stream with a prolonged fair-weather flow, and one not subject to violent floods.

Next higher in the scale, and suitable for the same conditions, is the drystone weir, where the brushwood and sods are omitted, and the mass is built of drystone, which should consist of large angular stones fitted to bond with each other and faced with the largest ones. It also is likely to be washed away unless solidly constructed, as shown in Fig. 52, and its height and the flood depth are small. Sometimes the crest is made wider to increase the stability of the weir, but this also decreases its discharging power by the added frictional resistance to flow.

FIG. 52

SECTION OF DRYSTONE WEIR



Occasionally, the stone is confined in place by galvanised wire netting, but this may deteriorate under water or be injured by the passage of boulders over it. Silt often penetrates into the interstices between the stones of drystone weirs and makes them fairly water-tight.

Crib weirs are a superior form constructed chiefly in America, where wood is plentiful. The cribs are rectangular and hollow frameworks, which are built up of roughly-wrought logs placed across each other in alternate layers and spiked together; they are put in position and then filled with stone. Their life depends upon that of their timber, and is thus not very long, especially in the tropics. As failures of some of the cribs may occur early, this form of weir is not permanent, and is not suitable for a large canal.

The design of the drystone weir may be followed generally for waste weirs of small tanks and escapes of small canals which have only a small flood depth (2 feet or less) over them, but a considerable fall in soil (from 5 to 10 feet) below them. In such cases might be formed a drystone or masonry bar crest at full-supply level, a downstream slope (2 or 3 to 1) pitched with heavy stones close-jointed and laid on quarry spauls (or covered with concrete), and a masonry toe wall (founded sufficiently deep to withstand erosion), with a boulder talus.

There are various forms of wooden and iron weirs—shutter, trestle, and mechanical (such as the Bear Trap (Fig. 110, p. 456)—which are chiefly in use in America and on the Continent of Europe, but are practically not employed on non-alluvial works in India. They require skilled labour to erect and repair them; they are of a temporary nature and costly in maintenance; and they are not suitable to resist the action of heavy floods. There is no more permanent and easily worked kind of weir than one constructed of masonry, and this form will now be considered.

132. Site of Intake Weir.

(*a*) *General Remarks.*—As in the case of a storage weir, an intake weir should, if possible, be built where the river is wide, so that sufficient length may be obtained for it to pass off floods with a small depth in order to avoid flooding riparian land upstream, and excessive overfall action on the foundations. Where the length available is small, the flood depth will be great, and high canal headworks and weir flanks may be required on account of the increased flood level. Good rock foundations are essential, and when the action of the overfall is considerable, either owing to its height or volume, the foundations will require protection by a water cushion (Art. 32). A great amount of backwater storage is not essential, as the canal supply will be furnished by the river flow, unaided or supplemented from storage; but a fairly large backwater is desirable, so that fair-weather freshets may be impounded thereby, and stored water may be passed down to it in bulk at comparatively long intervals, which will save loss in transit and obviate the necessity for constant regulation of discharge.

The site of a weir must, of course, be suitable for the physical conditions of the canal to be supplied by it (Art. 113 (*a*)). A weir should not be placed much higher up the river than is necessary to obtain command of the irrigable area, or else the canal from it may have to be dropped down at intervals in expensive falls or rapids. The higher up the river is the weir, the less is its catchment area, and thus possibly also the smaller and shorter is the flow which is to be utilised by the canal; on the other hand, the floods to be discharged will be decreased. The larger is the average area commanded per mile of the canal, the cheaper generally will be the project.

A weir should, if practicable, be located below the inflow of a large tributary and some distance from that of the nearest one downstream, so that the canal may not have to cross the former, and will be led over the latter well above its junction with the main stream: thus there will be a saving in the cost of the cross-drainage works.

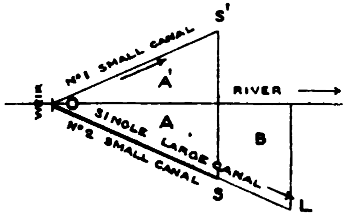
A good site for a weir is at the head of a rocky rapid in the river, so that the flood level downstream may fall rapidly, and thus be below the canal head and not affect it, and so that the canal may quickly gain command. The weir should, however, not be placed at the immediate head of the rapid, as there it would be exposed to the high approach velocity induced by the steep descent of the water, and possibly to undermining by retrogression of levels (Art. 116 (*b*)). If a water cushion has to be built, the weir should be still further retired to afford sufficient space for securing that from similar damage.

The work should preferably be situated in a straight reach, so that the floods may have a direct approach to and exit from it; this will increase its discharging power to the maximum possible by making its whole length equally effective, and will lessen silting behind it. Upstream of and at the weir the river banks should be high, so that expensive flood embankments and flank works will not be required (Art. 31). From a little downstream of the weir the banks should be only slightly above river flood, so that the canal head will not be in deep cutting for a great length. Where the river bank is low upstream, flood embankments will have to be constructed to prevent the weir being turned by floods, or much valuable riparian land being submerged ; they should be aligned out of reach of rapid flood-flow, and on high ground to reduce their cost. If the river bank is low downstream, floods will have to be kept out of the canal by a flank embankment ; this also should be retired from the limit of direct flood-flow.

(*b*) *Double Command of Weir.*—The most favourable site for a weir is where it can command land on both sides of the river. Treated simply as a mathematical problem on the assumptions that throughout their courses the canals will traverse country of the same character, and diverge uniformly at the same inclination from the river, the cost of a single large canal, OL, on one side of the river, will be 1·414 times that of the two small canals, OS and OS′ combined, one on each side of it, together commanding the same extent of irrigable area (Fig. 53). The explanation of this is that each portion of a canal has to provide the supply required, not only for the area it serves, but also for the whole area downstream of that. In the case of a long canal with the bulk of its irrigable area at the tail, the additional sectional area in the head portions thus necessary is much greater than the similar area of the two short canals. Similarly, the loss in transit, which bears a relation to the total sectional area of a canal, will, on the same assumption, be greater for the single large canal than it is for the two small ones. Moreover, the latter will have on the whole the shorter distribution system, which will thus be less costly in regard to expenditure both of money and water. Against these advantages of the two small canals may be placed the disadvantages attending the construction of the head section of the second one, which will probably be in more

FIG. 53

DIAGRAMMATIC CANAL PLAN



difficult country, A′, involving more execution of earthwork and crossings of tributaries where their catchment is at a maximum, than will be required at the equivalent tail portion, B, of the single large canal; also there will be the administrative inconvenience of having the irrigated area divided by the river. No general rule can therefore be laid down as to which of the two alternative canal systems is the cheaper and better, and they should therefore both be examined in any particular case. Unless, however, the physical conditions are much against the construction of the second small canal, the probability is that the single large canal will be the dearer and less desirable of the two alternatives.

(*c*) *Canals in Series.*—Ordinary weirs may be built in series, each with a canal or canals led from it. The advantage of such a system of works is that the seepage water returned from the upper irrigated land is picked up by the lower weirs and utilised in the lower canals. The disadvantages of such a series are that it is difficult to divide the total flow available among them, and that they are expensive on account of the number of headworks and canal head sections involved.

133. Design of Intake Weirs.

(*a*) *Alignment.*—The alignment of a weir will depend upon the nature of its foundations; but, if practicable, it should be carried straight across the river bed, as the work will thus have the most effective discharging power per unit of length, the flow over it will take place regularly, and silting behind it will be uniform and the least in amount. If a straight alignment is too costly, the weir should be set out in straight lines, united by gentle curves.

(*b*) *Foundations.*—Masonry overfall weirs require the best foundations, owing to the heavy pounding action on them of the water falling over the crests; the works should therefore have their foundations carried well into sound rock. When a weir is over 20 feet in height, its base should be protected by a water cushion (Art. 32), unless the depth of the tail surface of the natural river against it renders this unnecessary. A water cushion may be wanted when the weir is built just above a rapid (Art. 37 (*b*)), as there the downstream depth of the river is likely to be small.

The necessity for commencing the lowest part of the foundations first, in order to work under the least water pressure, etc., has been noted in Article 37 (*c*). Care must be taken to set out the lowest courses correctly, so that one does not run into another in a long work.

If a weir becomes undermined, it should be underpinned as soon as possible, otherwise the cavity may be largely increased by the swirl and pounding of the water, and the work may be breached. The underpinning should be done in short sections, separated from each other by undisturbed portions; all loose rock should be removed, the space thus left filled with fine concrete gauged with cement and rammed tight, and this should be protected by a masonry facing built in the line of the profile of the weir.

(*c*) *Mean Width.*—The mean width of a masonry weir 10 feet in height above its foundation, and with a flood depth over it of not more than 5 feet, may be made three-quarters of its height, and that of a lower weir a little less. For a higher weir, and for one with a greater flood depth over it, its section should be calculated by means of a stability diagram. The diagram should take into account the water pressure when the water upstream of the weir is at its crest level and the river bed below is dry, and also the upstream and downstream pressures due to the maximum flood. The former condition will usually be the one producing the greatest resultant pressure. In all cases the head expended in producing the velocity of approach of the stream (Art. 55) should be calculated and added to the statical head.

The following table gives the top, bottom, and mean widths

Consecutive No.	Height of Weir.	Width of Weir.			Depth of—	
		Top.	Bottom.	Mean.	Flood on Crest.	Tail Water above Rock Surface.
	Feet.	Feet.	Feet.	Feet.	Feet.	Feet.
1	5	2½	5	3¾	5	3
2	7½	3	6¾	4⅞	5	3
3	10	5	10	7½	5	3
4	10	6	11	8½	7½	4
5	15	7	14½	10¾	5	3
6	15	7½	15	11¼	7½	4
7	15	8	15½	11¾	10	5
8	20	7½	17½	12½	5	3
9	20	8	18	13	7½	4
10	20	9	19	14	10	5

of certain weirs to meet the conditions therein stated. In designing them the weight per cubic foot of masonry was taken as 140·4 lbs., or 2¼ times that of water, 62·4 lbs., the upstream face as vertical and the downstream one battering uniformly throughout at 1 in 2; more correctly the weight of silt-laden water should be taken into account (Art. 72, end of (*d*)). In ordinary cases the depth of the tail water will exceed that of the flood on the crest, and thus the resultant pressure will be thrown more upstream than it is in the above examples, where it is already at or a little within the middle third of the base. The weirs being comparatively low, the resultant might, without danger, be allowed to fall a little outside the middle third.

(*d*) *Batters.*—In Article 34 it is pointed out that a masonry dam is not given greater stability by building its upstream face with a positive batter, but that for low dams a negative batter to that face will increase the stability of the work. It will be better, however, to have neither batter for the upstream face of a weir, but to build it vertical, as a negative one would make the work retard the flow over it (para. (*e*)).

The downstream batter will depend partly on the crest width of the weir, and that should therefore be selected so as to allow of a suitable inclination to this face. The downstream batter of a low weir should not be less than 1 in 4; that for a high one should not exceed 1 in 2, partly to avoid the pounding of the face by the overfall, and partly for constructional reasons, as the face stones should be laid normally to the batter, and with a greater bed slope than ½ to 1 they cannot be built unless supported at once by backing, as otherwise they will slide on their beds. Within this limit the greater the batter, the smaller need be the section of the masonry.

Some weirs have been built with a curved profile downstream, so that the water may glide smoothly over them, and be delivered at the base tangentially to the bed of the stream. There it will have a horizontal velocity nearly equal to the vertical one due to its free fall; this is considered to be an advantage where logs and ice are liable to be carried over the work. Other weirs have had a stepped profile given to them downstream, so as to break the total fall into a number of small ones, and thus lessen the shock on the foundations.

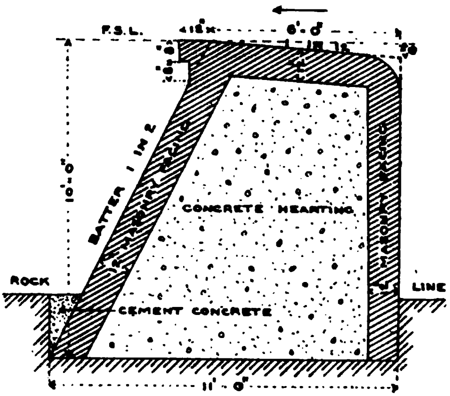
Neither of these profiles seems suitable for heavy flood discharges; the first will produce a considerable amount of scouring action, and the second will jar the masonry, especially if the water in descending leaps over certain steps, and thus falls with increased violence on the others, as it is likely to do when the flood depth is great. A proper design should protect the work from flood action by having a water cushion to absorb the force of the overfall, and by adopting a downstream batter which will retire the face of the masonry so as to avoid the direct impact of the overfall.

(*e*) *Crest of Weir.*—The top width of the weir should be regulated, so that with the limiting batter of the downstream slope it will make the weir of the full section required for its stability. The height of the crest should be as low as practicable, so as to diminish the amount of overfall, and the height of the flood embankments, if any, but should not be less than the full-supply level of the canal. It may exceed that if additional storage is wanted.

In cross-section the crest should rise downstream with a small slope, say, of 1 in 12, and should be united by a curve to the upstream face so as to give floods passing over it an upwards scouring action, which will lessen the deposit of silt near the weir, and also will carry logs, etc., over the work. The crest should be continued by corbelling of a total projection of from 6 inches to 1 foot beyond the top of the downstream face, so as to aid in discharging flood water clear of that face (Fig. 54).

FIG. 54

CROSS SECTION OF WEIR



In longitudinal section the crest should rise slightly (from 6 inches to 1 foot) from the canal to the other side, so as to divert the fair-weather flow of the river towards the canal, and also the flood discharge, which will tend to preserve a deep channel towards the head regulator and prevent excessive silting there. This is a cheaper device than splaying the weir downstream from the canal, and equally effective in securing the desired objects. (For oblique weirs see Article 30.)

134. Construction of Weir.

Generally, the cheapest form of construction of a weir is one consisting of masonry facings and a hearting of concrete. If the facings are of roughly dressed block-in-course, and the weir from 15 feet to 25 feet high, they may be laid in 9-inch courses, 12 inches long on the face, and 16 inches deep in the work, with headers 5 feet apart clear, and projecting 12 inches into the hearting, which are convenient dimensions for handling. If they are of rubble masonry, they should be at least 2 feet thick, and have headers at similar intervals, and projecting similarly into the hearting. The face joints should not be thicker than ½ inch, as wide joints are liable to be scoured out by the overfall, which will then tend to blow out the face work. Weirs built wholly of rubble should have the stones breaking joint in all directions, so as to secure greater water-tightness. The crest of the weir should be built of finely jointed and heavy stones placed with their length at right angles to it, so as to offer the least hold to the water and the greatest resistance to its uplifting action; or the work may be finished off in cement concrete between heavy stone facings.

The construction of the weir should proceed from the lowest level uniformly upwards. If the stream is in flow, the deepest section should first be shut off by a coffer dam, and then its foundations raised above bed level. The next lowest sections should thereafter be dealt with similarly. As the work rises, the stream should be diverted to pass over the sections alternately. If the weir cannot be completed in one season, a large gap should be left near its centre so that floods may be discharged at a low level over the rest of the unfinished work. The crest of this gap should be a little above the sill of the scouring, etc., sluices, so that finally its masonry can be completed after the flood season by passing the fair-weather flow through the sluices.

135. Weir Backwaters.

Some weirs eventually silt up practically level with their crests, others maintain pools upstream of them. In certain cases the silting takes place only in the neighbourhood of the weir (this is due to the widening of the backwater there); in others the bulk of the deposit is at the head of the backwater, where the velocity of the flow is first checked, while near the weir there is little (this is caused by the heading up of the river upstream, increasing its velocity of approach to the overfall).

This difference in behaviour is partly due to the nature of the silt carried down by the current, and partly to the scouring capacity of the stream, which depends upon the velocity of its flood discharge, and that on its cross-sectional area and longitudinal slope as modified by the weir. If the silt consists of heavy sand, the backwater widens out to the weir, and the gradient of the stream is not steep, excessive silting will probably occur. If the silt consists of fine clayey matter, and the stream flows in a narrow channel with considerable velocity, the backwater pool may be preserved. In the latter case the weir will not offer an obstruction sufficient to prevent scouring action from taking place after the stream bed upstream of it has been raised a certain amount by silting, and the further deposits which may occur temporarily behind it will be removed by subsequent floods. When a backwater silts up, it is useless to raise the crest permanently (Art. 99 (*e*)) with a view to restoring its storage capacity; that can be regained only by a temporary crest fixed after the flood season and removed before the next one.

It has been explained in Article 35 what small effect sluices have in removing silt; as that effect is local, it is necessary to construct them close to the place (e.g. the head regulator) to which a clear channel is to be preserved. It is of little direct use, as far as storage is concerned, to make the sill of the scouring sluices below canal bed level, as water impounded below that level will not pass into the canal. At the upstream part of the backwater, where the river bed is above canal bed, the lowering of the former will, however, add to the storage. It is, nevertheless, of indirect use to lower the sluices slightly, say, not more than 2 feet, so that they will tend to scour out the bed of the backwater below canal bed for a greater distance, thus providing more space for subsequent temporary deposits; also, they will thereby gain a more effective discharging head.

136. The Head Regulator and Flank Works.

(*a*) *Objects of the Work.*—The head regulator unites the weir to the canal, and thus forms part of the headworks. Its objects are:

(i) To shut out flood water from the canal;
(ii) To regulate the discharge passed into the canal.

To secure the fulfilment of (i), the top of the head regulator wall must be raised above the surface of the highest river flood expected. For small streams a safety margin of at least 2 feet above that level should be allowed; for large streams the margin should be at least 4 feet, and for rivers it should be at least 6 feet.

To obtain the power of regulation, (ii), the head regulator wall is pierced by sluiceways of sufficient size and number to admit into the canal with free flow its full-supply discharge when the backwater pool is at canal full-supply level. These sluiceways are controlled by sluices, which are raised or lowered as desired, and when fully closed are water-tight.

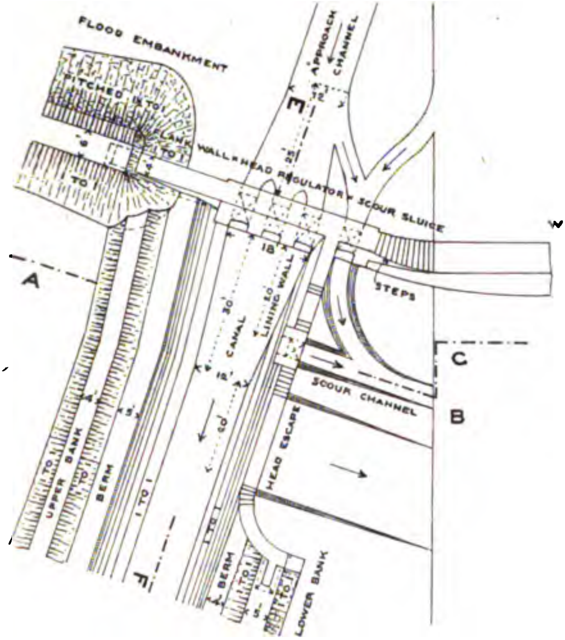
(*b*) *Alignment and Situation.*—The canal should be aligned so as to leave the river at an angle in order that it may pass out of the high-flood margin, and away from the banks as soon as practicable. If the banks are high, and the slopes of the country beyond are steep, the canal must be taken out at a small angle (Fig. 55); otherwise, to avoid getting into deep excavation, it would have to be turned sharply a little below its head in order to become nearly parallel to the river. If, however, the natural banks are low and the country beyond fairly flat, the canal should leave the river at right angles, and then be curved gently so as to become nearly parallel to it when out of the flood margin (Fig. 56). As the canal has to pass through the regulator wall at right angles, in order that the sluices may discharge symmetrically parallel to its centre line, that wall has in the first case to be aligned at a widely obtuse angle to the weir, and united to it by a small curve, while in the second case the regulator will be at right angles to the weir. In the first case the intake will admit the river flow into the canal with a small change of direction, and silting upstream of the weir should be little. The weir scouring sluice will, however, be at some distance from the regulator sluices, and thus somewhat ineffective in keeping a

CANAL HEADWORKS

FIG. 55

CANAL DIVERGENT ($\frac{1}{250}$)

PLAN



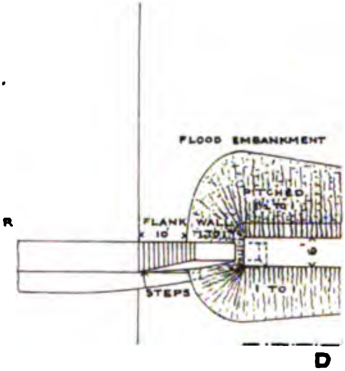
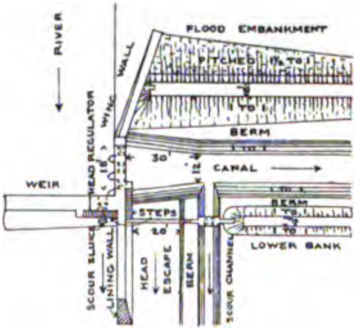


FIG. 56

CANAL NORMAL ($\frac{1}{960}$)

PLAN



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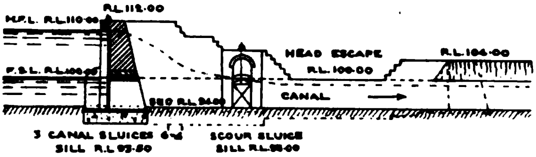

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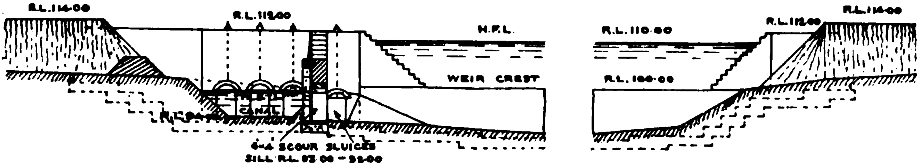


clear channel to them. In the second case, the water at the intake will have to flow at right angles to the river, and silting may thus take place at the regulator. The weir scouring sluice should therefore be placed so as to induce scour along the face of the regulator, and this should suffice to prevent silt being deposited near it.. The above are limiting alignments for the canal and head regulator, but intermediate ones can of course be adopted to suit the natural conditions.

As a rule, the head regulator is placed at the immediate flank of the weir. In certain cases, however, it is built at some distance upstream of that work, if deep water exists there, and excessive silting is likely to take place at the weir itself. The latter position may involve heavy double flank embankments at the head of the canal, in addition to the flood one at the weir, until high-flood margin is passed.

(*c*) *The Head Regulator.*—As close as practicable to the head regulator should be a scouring sluice, or sluices, pierced through the weir with sill level, say, 2 feet below canal bed. The headwall should be raised over both the canal and scouring sluices in order to carry their lifting gear, and so as to enable the former to be operated even during floods. This wall should thereafter be prolonged as a flank wall into the river bank, and in continuation should be a flood embankment, raised at least 2 feet above the masonry, pitched on the upstream side and extended till it meets the ground at its top level. The canal sluice vents should have a total waterway at full-supply level equal to that of the canal, so as to admit the full-supply discharge into it without afflux when the back-water pool is at weir crest level. The height of the sluices above canal bed should be equal to the depth of the canal, and the width of each should be about two-thirds of that. In order to permit of the future deepening of the canal, if such is likely to be necessary, the sills of the sluices should be 6 inches to 1 foot below original canal bed level, and the height of the gates increased by, say, half that amount. The gates are preferably made of cast iron, as this is the most durable and water-tight form of construction. Lifting rods are fixed to them, and these have at the top screwed ends which engage with female screws cut in capstan heads that are bolted to the top of the headwall. By the revolution of the capstan heads by means of a spanner the gates are raised or lowered; they travel on iron frames and between iron guides.

As the amount of silt carried down by non-alluvial streams is comparatively small in amount, the design of the regulator does not usually provide silt-reducing arrangements; all that is generally done during floods and when supply is not required is to close the canal sluices and open the weir scouring sluice, and also throughout the irrigating season not to admit more supply into the canal than is wanted for irrigation. If further silt reduction has to be effected, this can be done in the first case (Fig. 55) by building upstream of the regulator across the approach channel a small weir with its crest a little below canal full-supply level, so that it stops silty bottom water and supplies the canal with clear top water; the length of the crest of this weir has, of course, to be sufficient to pass the full-supply discharge of the canal.

(*d*) *Flank Wall.*—At the side of the weir opposite to the canal should be a flank wall raised to the same height as the regulator headwall, and having in continuation a flood embankment also of the same height as the one on the opposite side, and pitched similarly to it. These works should be aligned so as to get into high ground as quickly as possible, and thus will generally be in, or nearly in, a line with the weir and at right angles to the stream. On both sides the masonry flanks should have steps leading down to the weir crest.

(*e*) *Canal Head.*—The length of the headwall of the regulator has to be sufficient to allow the canal head to be constructed safely, and out of reach of the weir overfall and river floods. To reduce the length between the canal regulator sluices and the weir scouring sluice in the first case (Fig. 55), it is desirable to build a "lining wall" (rather than to construct a heavy flank embankment) parallel to the canal for a short length downstream from the regulator headwall, and with its top well above the high-flood level of the river downstream of the weir. In this wall a "canal scouring sluice" (with its sill at least 1 foot below canal bed) should be placed for the removal of any silt which might otherwise accumulate inside the canal at its head. This sluice can also be utilised to lower the canal level when necessary. To permit of the automatic return to the river of excess supply admitted accidentally into the canal, it is advisable to have a "head escape" in the canal soon after it passes out of the reach of high floods; the crest of this escape will be at canal full-supply level, and should be at least 1 foot above river high-flood level. Where the levels permit, this escape can be built in continuation of the lining wall (Fig. 55), and this will remove the head of the canal downstream flank embankment or lower bank further from the weir. If that embankment still lies within the high-flood margin of the river, it should have its top carried to at least 4 feet above flood level and its river slope heavily pitched.

In the case of the normal canal (Fig. 56) it is also generally best to have a lining wall, rather than a heavy downstream bank, to shut out river floods. The head escape and canal scouring sluice can then be placed near the head regulator if the river bed falls rapidly from the weir, and can have their outfalls back into the river downstream of the end of the lining wall.

137. Single- and Double-Bank Canals.

(*a*) *Single-Bank Canals.*—For this type only one bank is constructed, and that on the downstream side of the canal, so as to prevent breaches or overflows which would waste the supply and flood the country below them. This form is adapted only to steep sidelong ground, where the water spread of the canal will not be great, as it would be were the cross slopes of the country gentle, in which case there would be much loss from evaporation and absorption. In a single-bank work the drainage from the lands upstream passes into the canal, and the discharge of the minor streams crossed and blocked is admitted into it. From both these sources external silt is deposited in the canal, and excess water will come into it after any run-off from rainfall. This drainage is passed out of the canal either at masonry (Art. 147) or natural escapes (Art. 148); to enable it thus to be dealt with safely, the bank has to be raised higher than is required for the ordinary full-supply flow. Even then breaches are likely to occur from the inflow of storm water, as it is difficult, especially at night time, to arrange at once for opening numerous escape sluices when rain falls suddenly. Moreover, a single bank does not protect the canal from being choked with dust blown in by strong winds from the pulverised surface of neighbouring land. The removal of the deposit of silt leads to extra cost in maintenance, and its irregular deposition on the bed may affect the discharge of the canal.

The sole advantage of a single-bank canal is its initial cheapness, but if the risk of breaches and the extra cost of maintenance were taken properly into account, this would disappear to a great extent, or wholly. For this reason most modern canals are made with double banks.

(*b*) *Double-Bank Canals.*—In this type a bank is formed on the downstream side to prevent breaches, and another on the upstream side to shut out flood water. The canal is thus preserved from external influences, the flow of water down it can be regulated as required, the danger of breaches from excess supply is minimised, and the ingress of silt from drainage is prevented.

Field drainage is diverted from such a canal, where necessary, by catchwater drains (Art. 161) to the main drainage lines, or is collected and led over the canal at intervals by small pipe superpassages or into it down inlets (Figs. 78 and 79, p. 310). The first-named arrangement is preferable, as it does not entail damage to lower lands or to the canal.

The streams crossed by the canal are either led under it at aqueducts, culverts, or slab drains, or are passed over it by superpassages or siphons, and occasionally are admitted into it at pick-up weirs or inlets. All these are called cross-drainage works (Chap. XI).

Double-bank canals are necessarily more expensive to construct than single-bank ones, but their greater security and smaller cost of maintenance are generally sufficient to justify their construction.

138. Canal Sections—Setting Out.

(*a*) *Cross-Sections.*—In Article 117 minimum side slopes for excavation and embankment were given; in Figs. 57–60 are drawn typical sections of a non-alluvial canal. These sections show how greatly the banks vary in size according to the level of the canal bed with reference to the ground surface, and how their cost increases with the elevation of the former. The embankments of such a canal are here discussed, as their section and construction differ somewhat from those of an alluvial canal, on account of the nature of the soil available and the frequency of cross-drainage works. The top-width should not be less than 4 feet, and the top of the embankment should not be less than 2 to 3 feet above

CANAL TYPE SECTIONS

FIG. 57

WHOLLY IN EXCAVATION

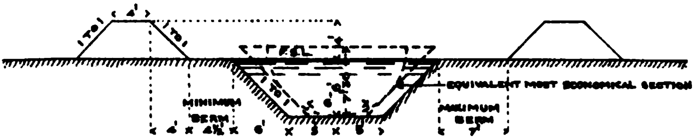


FIG. 58

PARTLY IN EXCAVATION

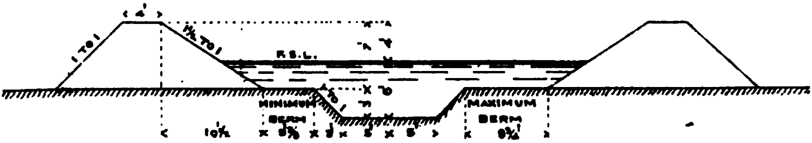


FIG. 59

IN LOW EMBANKMENT

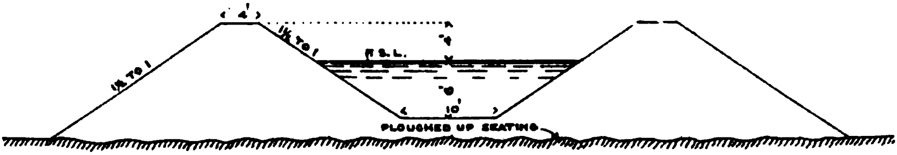
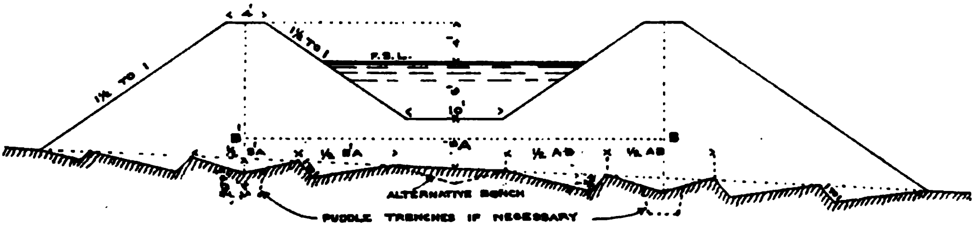


FIG. 60

IN HIGH EMBANKMENT



canal full-supply level in the case of small, nor less than 3 to 4 feet above it in that of large canals. High and important parts of the embankment should be raised a little higher than the ordinary sections, so as to be less liable to breaching.

At all cross-drainage works the banks for a minimum length of 20 feet from them should be raised at least 2 feet higher than the top of the walls against which they abut if those have been carried up only to a safe height above maximum water level, so as to make the earthwork equally secure. Thereafter the embankment top should be ramped down to ordinary level at an inclination of, say, 1 in 20. This raising is necessary to prevent at such works the occurrence of breaches, as there these will be specially difficult to repair soundly and water-tight. The top 2 feet of the embankments cannot be relied upon to withstand water infiltration, as the earthwork there is liable to crack under the influence of sun and wind.

(*b*) *Setting Out.*—The centre line of the canal should first be set out and then lock-spitted. At intervals of from 50 to 100 feet the side-widths of the excavation and the top-width and toes of the canal banks should be marked, and the corresponding lines also lock-spitted. After the excavation has been roughly taken out (Art. 121), excavation templates, about 12 inches wide and from 50 to 100 feet apart, should be trimmed true, and thereafter the final slopes should be dressed to them. For the embankments profiles should be set out at the same intervals: a peg should be driven into the ground at each toe, and bamboos or poles fixed to represent the top-width, and the level of the top should be marked on them. For each profile a string should be tied from one ground peg to the mark on the nearest bamboo, then to the similar mark on the other bamboo, and finally to the peg on the other side. As canal banks are generally low, allowance for settlement is not usually made, but for high and important embankments it is advisable to provide for it in setting out and construction.

139. Canal Embankments.

(*a*) *Construction.*—As much care should be taken to form the embankment as is necessary in the case of an earthen dam having the same pressure of water against it. When carefully made, an embankment leaks less than does a cutting in ordinary soil (Art 18 (*b*)).

For banks of less height than 5 feet from ground level to canal bed, and where the ground is sound and not pervious, it will generally suffice to plough up the natural surface, and to remove all roots and shrubs, so as to form a reliable seating for the embankment (Fig. 59). In banks of greater height, and where the subsoil is pervious, small puddle or key trenches below each of the banks are advisable (Fig. 60).

On steep sidelong ground and under high embankments the natural surface should be cut into a series of V-shaped benches (Fig. 60). These might have a total width of from 8 to 12 feet, and a trough depth of about 1½ feet. Next the centre line of the bank the slope of the bench might be 1 to 1, and on the other side it should be flatter, so that the effect of the benching will be to make the earthwork tend to move towards the centre of the embankment and compress itself rather than away from it and slip (Art. 86 (*b*)).

The embankment should be constructed of its full width in level layers not exceeding 6 inches in thickness. All clods should be broken up, and the earthwork consolidated by rammers, and in the case of important banks by rollers. Slightly watering the completed layers would be an improvement, but would usually be too costly a measure to adopt. After the bank has reached 1 foot above canal full-supply level, less attention to its consolidation is necessary.

Particular care should be taken at all junctions of the embankment with masonry works to secure perfectly water-tight connections. In regard to the masonry the design should provide for staunching walls, etc., while for the embankment the most impervious soil available should be used; this should be freed from all porous material, should be slightly wetted and well consolidated, so as to abut tightly on to the staunching walls.

(*b*) *Material.*—For ordinary banks, the material of which they will have to be formed will, for economical reasons, have to be that derived from the canal excavation, or from borrow pits dug in the immediate neighbourhood. For important banks it may be necessary to align the canal so as to bring it on to soil suitable for their construction.

For low banks all soils which are not powdery, peaty, sandy, slushy, or charged with salts, will suffice. For high embankments the best material is one which consists half of clay, half of grit. The most clayey soil should be placed in the centre of the bank, and the gritty soil outside of this.

The surface of the slopes of low banks should be formed of fertile soil (usually the original top soil, which should in that case be reserved for the purpose), so as to encourage the growth of grass for the protection of the slopes from guttering by rain, etc. For high banks, for the same purpose, it may be necessary to form the surface with grit mixed with the fertile soil. Turfing the slopes is generally too expensive, but, if required, the slopes may be sown with grass seed.

(*c*) *Maintenance.*—Embankments should always be maintained to full section, rain scores filled up, large shrubs and coarse grass rooted out, cracks, rat- and crab-holes dug out and refilled, drainage attended to, and, generally, all petty repairs effected as soon as possible.

Leakage should at once be stopped. Where there is defined leakage, the defective part should be cut out and re-made with water-tight material well consolidated; in bad cases a puddle wall or puddle trench should be constructed. Where the leakage is undefined, and the earthwork generally too porous, it can be rendered staunch by damming the section of the canal, throwing in clayey soil, stirring it up, then draining off the water and treading the bed by men or cattle, and repeating the process as may be necessary to puddle the canal.

CHAPTER XI.

CANALS IN NON-ALLUVIAL SOILS—REGULATION AND CROSS-DRAINAGE WORKS.

140. General Remarks.

(*a*) *Classification of Works.*—A canal has to be provided with regulation and cross-drainage works; the former are required for controlling the discharge or improving the alignment of the canal, while the latter are wanted to deal safely with the flood discharges crossed by the canal. The only other works which may be necessary are locks for navigation canals (Art. 11) and bridges (Art. 127) for cross-traffic; these might be termed communication works, and not being, strictly speaking, irrigation ones, and their design having little to do with irrigation, are not noticed here. The intake weir and head regulator also come under the head of regulation works, but on account of their importance have been separately described (Arts. 131–136). The remaining works usually constructed, as classified under the two heads mentioned, are:

A. Regulation Works.

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149.	Tail Escape	288

B. Cross-Drainage Works.

Article. Page.
154. Aqueducts—arched, trough, or pipe.. 295
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157. Superpassages 300
158. Siphons 304
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160. Intercepting Weirs and Reservoirs .. 307
161. Catchwater Drains 309

(*b*) *Character of Works.*—As the works are expensive to construct, the alignment of the canal should be chosen carefully, so as to reduce their number and cost to a minimum. They should be of a permanent character, both in regard to the nature of their construction and of their design, so that they will be durable and cost little to maintain, while it should not be necessary to alter them extensively when expansion of the canal becomes necessary (Art. 109 (*a*)).

In certain new countries the works, for the sake of initial economy, are often constructed of wood, where that is abundant and cheap. Iron structures have also been erected, but in the outlying districts, through which canals usually run, the maintenance of these is costly and difficult, and they cannot be said to be really permanent. Both wood and iron are unsuited to districts liable to be visited by forest fires, which would rapidly destroy them. It would therefore seem better to restrict their use to replaceable portions of the works for which they alone are adapted, such as sluices, or to works which cannot well be carried out in masonry, such as long and deep siphons.

Masonry (including in the term stonework, brickwork, concrete, and reinforced concrete) is decidedly the best material to employ. Stone is the most durable and sightly, and should be used where cheaply available. It is not necessary to build with large stones finely dressed, as the works will generally be in the districts ; only the essentials of sound and economical construction should be aimed at, and for these rubble and rough-coursed masonry will suffice.

For foundations and the heartings of thick walls, concrete is amply good enough ; it has the advantage of being monolithic, and thus free from joints, which might allow of leakage.

A. REGULATION WORKS.

141. Regulators.

Where a large branch takes off from the main canal, a regulator should be built at the head of the former, so that its discharge may be controlled as desired. It is better also to construct in continuation of and generally at right angles to it a regulator across the main canal, so that when necessary this may be closed, partially or wholly, to force water down the branch. By this arrangement, either the branch or the main canal (if the former is large enough) can be closed entirely, when it becomes necessary to practise economy in distribution by a system of rotation of supply (Art. 23 (*b*)). These regulators should be similar to the head regulator (Art. 136) in having sluiceways equal in area to the full-supply waterway of the channels below them, and these should be closable by iron sluices controlled by lifting apparatus.

As usually the branch takes off at right angles from the main canal, the flow down each channel when unobstructed at the head will not be in exact proportion to the waterway through its regulator, since the water passing down the branch has initially to change its direction through a right angle. In some cases, where a right to a fixed share of the supply has to be complied with, it is necessary that the division of the water should be automatically and visibly made, no matter how its level fluctuates. This can be arranged for by making at the place of division the main canal and the branch bifurcate at the same small angle from the main canal upstream, and with their sills at the same level, so that the flow down each is proportionate to the waterway of its regulator (Fig. 120, p. 486).

It is generally inadvisable to have an obstruction, such as a regulator, across a canal, as this, by checking the velocity of flow, tends to cause silt to deposit upstream (but see Art. 223 (*b*)). If the obstruction is merely of temporary duration, very little harm occurs, but if it is long continued, silt may be deposited, and this may be of a tenacious, clayey nature and thus difficult to move. In this latter event the obstruction should be removed at intervals, and a flushing discharge of clear water passed down to remove the silt, the process being assisted, if required, by stirring up the silt by harrows, etc., drawn along the bed. In small canals silt is thus loosened and carried down by dragging along them bundles of thorns weighted with stones.

142. Outlets.

(*a*) *General Remarks.*—Outlets should be located where the ground is hard, so that they may be securely founded. As a rule, they should be placed where the canal full-supply level is below ground surface, as this will reduce the cost to a minimum, and will also make them more staunch.

The sill of the outlet should ordinarily be placed so as to give the full-supply discharge of the distributary when the canal is at a low level, although this will diminish the area under command; the steeper the general cross fall of the country, the less will the lowering of the outlet sills diminish the irrigable area. It is, however, advisable to keep the sills of the outlets at the head of the line well above canal bed, so that sufficient water may pass automatically to the lower outlets.

The more numerous outlets are, the easier is it to irrigate small areas. On the other hand, every outlet is a source of expense, and may cause leakage and breaches. These conflicting conditions are best met, where there are numerous outlets each irrigating a small area, by a series of "parallel distributaries" (Art. 232 (*a*)). Generally, an outlet should not serve less than 50 acres.

Outlets should not be used as escapes for flood water, as the extra discharge thus passed down them would damage the distributaries, and, moreover, being comparatively small, would not afford much relief. They should be simple, durable, water-tight, and cheap in construction, and their regulating apparatus should be capable of being locked to prevent them from being tampered with by persons unauthorised to work them. This can be done simply by chaining and padlocking the lifting rod to the capstan head.

General matters in connection with outlets and distributaries are discussed in Articles 224 and 231 (*d*).

(*b*) *Type Designs.*—A few of these are shortly described below:

(i) *Headwall Outlet* (Fig. 61).—In this a masonry wall is built on the centre line of the canal bank, and has its flanks continued well into the earthwork, so as to secure a staunch connection with it. The top of the wall should be raised at least 1 foot above canal full-supply level, and the flanks a foot higher still. The wall has in it the outlet vent, which on the upstream side is closed by a small wooden shutter controlled by a locked regulating screw, worked from a capstan at the top of the wall. This form is suitable for an outlet in deep excavation; it interferes with the inspection path, but that could be carried over the distributary channel on a small cheap footbridge or pipe drain.

(ii) *Slab Drain Outlet* (Fig. 62).—In this type the outlet passage is carried under the canal bank as a slab drain; at the upstream end of this is a headwall with the regulating apparatus, and if it is desired to shorten the slab drain, a tail wall is built at the downstream end. If the slab drain is long, a staunching ring can be constructed round it on the centre line of the canal bank; the inspection path is led on that bank across the outlet. This form is suitable for an outlet in shallow excavation.

(iii) *Pipe Outlet* (Fig. 63).—If for any reason an outlet has to be placed where the canal is chiefly in embankment, i.e. where its full-supply is well above ground surface, the simplest form for it will be a pipe led through the embankment and carried on a foundation of concrete, or surrounded by that material, and controlled at its upstream end by a sluice of the waterworks pattern, or by a cheaper pole-and-plug arrangement (Fig. 43, p. 222*a*). If the earthwork is porous, a staunching ring should be formed round the pipe where it crosses the centre line of the bank.

143. Tail Reservoirs.

A tail reservoir is frequently of use as an adjunct to a canal in order to serve the following purposes:

(i) To impound stream discharge which would otherwise run to waste;
(ii) To utilise canal flow which would otherwise run to waste;
(iii) To diminish the sectional area and cost of the canal;
(iv) To render the flow available at times convenient for irrigation.

(i) When the source of supply is a stream, and the canal is short, such a reservoir can be utilised to impound the night flow, and make it available for use during the day. Also,

DISTRIBUTARY OUTLETS

FIG. 61

HEADWALL OUTLET

ELEVATION

SECTION ON AB

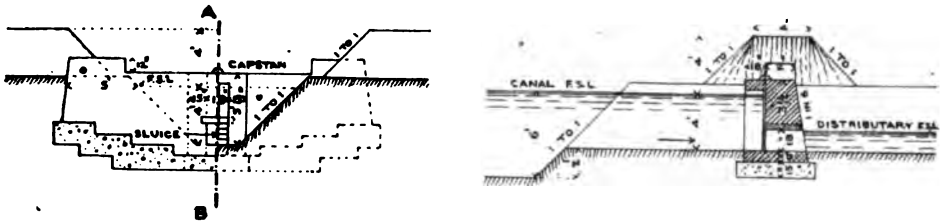


FIG. 62

SLAB-DRAIN OUTLET

PLAN

SECTION ON AB

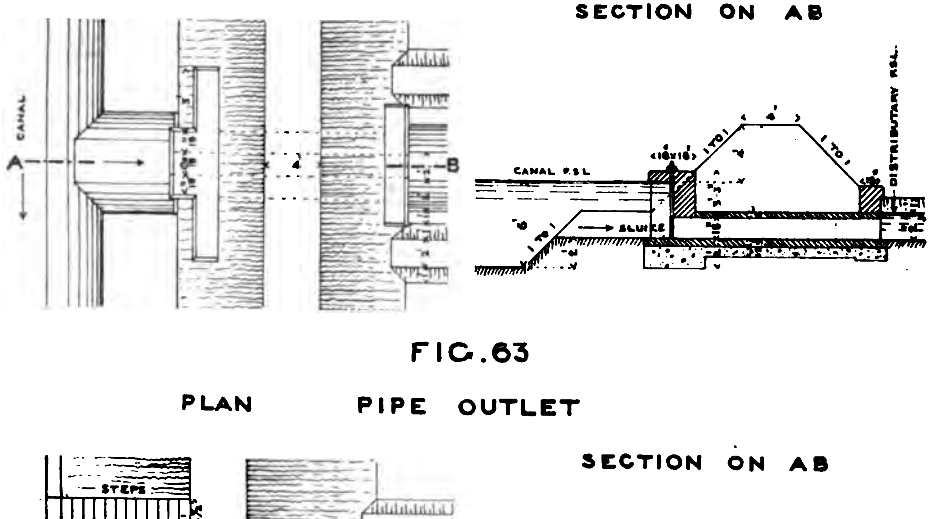
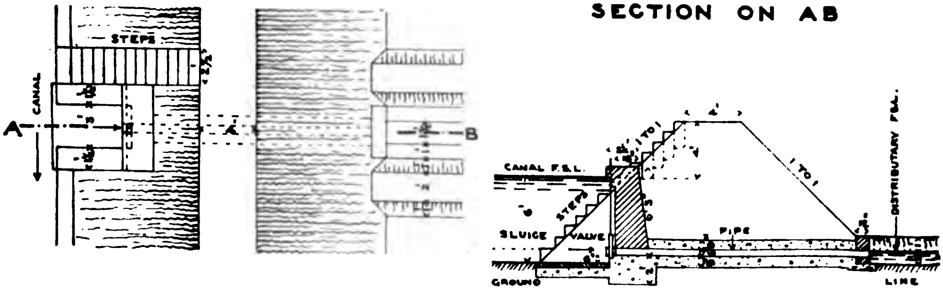


FIG. 63

PLAN

PIPE OUTLET

SECTION ON AB



when irrigation water is not required, such as after heavy rainfall, part of the flow of the stream can be impounded in the reservoir for subsequent use.

(ii) In a long canal it may not be easy to regulate the discharge so that it may be utilised fully, and thus, occasionally, water may have to be run to waste at the tail. If a tail reservoir has been constructed, such water can be passed in it, and can afterwards be used.

(iii) As the area commanded by a canal per mile run is generally greater at the tail than at the central part of its length, and still greater than it is at the head, the upper sections of the canal have to be increased considerably to afford supply for the lower sections beyond that required for themselves (Art. 132 (*b*)). If, however, a tail reservoir is constructed for the supply of the lower sections, the upper ones can sometimes be reduced so as to suffice alternately only for the irrigation under the former and the latter, whichever is the greater of the two demands (see (iv) below).

(iv) By means of a tail reservoir all the irrrigation can be conducted in the day-time, which is an advantage. Moreover, when a sudden demand for water arises, as after a prolonged closure of the canal, such a reservoir may be able to meet it, and thus obviate the necessity for increasing greatly the upper sections of the canal to cope with it. It is, of course, not essential that the reservoir should be placed at the extreme tail of the canal. It should be made where there is a suitable locality for its cheap construction, such as a natural depression, which will effect a considerable storage at a low rate. The capacity of the reservoir should be sufficient to enable it to serve the purposes above described.

144. Vertical Falls.

If the natural slope of the country is steeper than that of the longitudinal slope of the canal, to prevent the canal from working out above ground level its bed may have to be dropped at intervals to suit the natural contour by means of vertical falls, which are really overfall weirs. In Northern India, for the large alluvial canals elaborate " notched falls " have been devised to meet the conditions existing there (Art. 225 (*b*) (v)). For small canals in non-alluvial soils, simpler and cheaper arrangements are sufficient.

The depth of drop to be given to a vertical fall depends partly upon the slope of the country, and partly upon the nature of the subsoil, and should usually be such that the cost of the work and the consequent extra expenditure entailed by deepening the canal downstream are together at a minimum. As general limits for the depth of the drop 4 feet as an average, and 8 feet as a maximum, may be taken ; it is also advisable to fix a limiting minimum depth of excavation for the canal upstream of the fall. To reduce the cost it is best to locate the work at a place where the soil is of medium hardness. It may also be desirable to construct a fall where a road bridge, canal regulator, or other work is required so as to effect economy by having a combined structure to serve the two purposes.

When water falls over a weir of full unobstructed width, it approaches it with increased velocity owing to the decreased depth on the crest ; with such a weir the velocity in the canal upstream would be unduly increased, and scour or "wire-drawing" (Art. 149) of the bed and erosion of the sides might take place for some distance. To avoid this, either the crest of the fall should be raised or its length reduced, so as to maintain the flow at its ordinary rate. The latter alternative is preferred, as the former causes the canal to silt, and renders useless the excavation of the bottom of its bed, unless this has been purposely diminished to correspond with the effect of the raising of the crest. The length of the crest to be allowed, to prevent undue acceleration of flow, is, however, not a constant one ; it is at a maximum when the canal is at its highest level, and decreases as that level lowers. In the simple form of vertical fall sketched in Fig. 64, this reduction of length can be effected by dropping in needles so as partly to close the vent of the fall, the total unobstructed length of which is that calculated to be required to pass the full-supply discharge of the canal. To provide for the future expansion of the canal and for contingencies that length should be slightly increased between the masonry flanks, and should be reduced to its proper dimension by the insertion of needles. The needles should be fixed at intervals so as to break up the sheet of water flowing over the headwall.

After passing over the crest of the head or drop wall the water falls into a water cushion, the sides of which, in ordinary hard soils, may either be splayed or at right angles to the drop wall ; the former tend to create eddying motion, which is harmful

FIG. 64

VERTICAL FALL

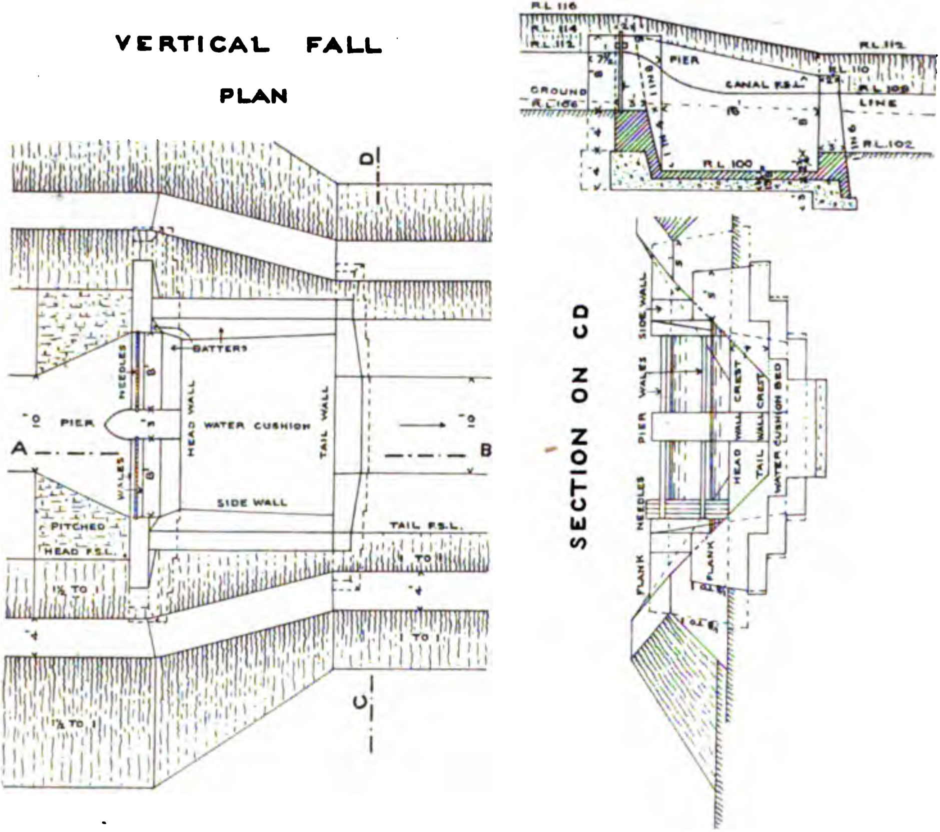
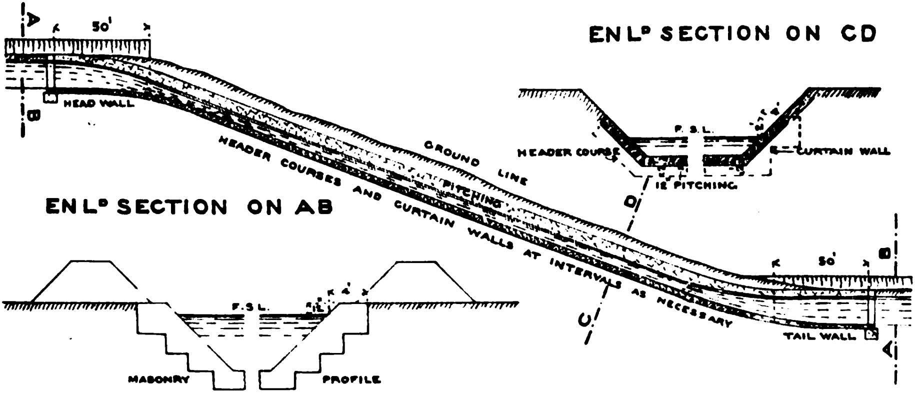


FIG. 65

SECTION OF RAPID



in the case of soft soils. The water cushion protects the foundations and regularises the flow of the canal downstream. Where a considerable total fall has to be negotiated, there is some economy in arranging the individual vertical falls in series, like the water cushions shown in Fig. 7, p. 56, so that a downstream one protects the foundations of that upstream of it, and the two form the ends of the water cushion between them.

A vertical fall can be utilised to obtain correct gaugings of the discharge of the canal easily.

145. Rapids.

Where there is a considerable and sudden drop of the country and the ground is hard, as it usually will be at such a place, instead of a series of vertical falls to suit it, which would be expensive to build, a rapid (Fig. 65) may be constructed. If the unprotected ground is not sufficiently hard to withstand the velocity of the flow due to such a descent, the bed and sides of the canal for 2 feet above its full-supply level should be securely pitched. In the case of large canals it may be necessary at intervals to build curtain walls across the section of the rapid, to equalise the flow down it, and to have header courses in the pitching to prevent its displacement. It is as well to keep the bed-width of the rapid at least equal to that of the ordinary part of the canal, so as to diminish the depth of the flow over it, and thus the scouring power of the water, and to make the surface of the pitching somewhat rough, so as to decrease the velocity of the discharge. Where the soil is hard, but not sufficiently so to resist undermining water-lap action, it can be adequately protected against that by laying the pitching on a 6-inch layer of quarry spauls, etc. The pitching should be continued for some length upstream and downstream of the rapid, so as to destroy the extra velocity produced by it, and to protect the bed and banks of the canal from damage thereby.

146. Tunnels.

On account of the expense and difficulty of construction of tunnels, they are seldom driven for irrigation canals. A tunnel may be necessary when a reservoir is on a different catchment from that of the irrigable area, and is indicated when a comparatively narrow but long ridge with cross spurs has to be passed, as the work may thus save many times its length of open channel in falling contour and with numerous cross-drainage works, and the consequent losses in head and in transit. A tunnel is best located in hard rock, as then it will not have to be lined ; if excavated in softer material, which will disintegrate under the action of water, lining will be necessary, and that is difficult and expensive to construct. The lining should be in water-tight connection with the natural backing. If the lining is of masonry, this can most easily be effected by cement grouting under pressure between it and the excavation ; if it is of concrete, that should be rammed tight on to the excavation ; if it is formed of concrete slabs, these should be bedded on and set in cement mortar.

A tunnel should be given as steep a longitudinal slope as practicable, so as to increase the rate of flow through it, and thus to diminish its sectional area. If the tunnel is unlined, that area should be increased from 15 to 20 per cent. beyond the calculated amounts, to allow for the retardation of flow due to the roughness of its wetted perimeter. The alignment of the tunnel should preferably be straight, and if the work is of any length, should, if possible, afford sites for vertical shafts, so as during construction to increase the number of working faces and diminish the lead for the removal of the excavated spoil. If the estimated cost of the tunnel is greater than two-thirds that of the alternative open channel, the latter should ordinarily be selected for execution owing to the probability of a considerable excess being incurred on the former on account of unforeseen difficulties in excavation.

Minor advantages of tunnels are that they save maintenance charges, loss from evaporation, and, if in solid rock, loss by leakage, while if driven below a fissured stratum may tap subsoil flow. Moreover, when the canal has to be increased, it may not be necessary to enlarge an unlined tunnel, for, by bringing its interior to a smooth surface by cement plaster, its discharging capacity will be largely added to by the reduction of the frictional resistance to flow.

Tunnels have been made over 9,000 feet long and to discharge over 3,000 cusecs. In India there are none discharging over 2,000 cusecs, and few exist there ; the best known is the one from the Periyar Reservoir, Madras Presidency, which leads its storage on the west of the Western Ghâts through the divide to the irrigable area on the east of them ; its cross-section is 80 square feet, and its bed slope 1 in 75.

147. Masonry Escapes.

(*a*) *Double-Bank Canals.*—In double-bank canals escapes are regulating works in that they are required for the discharge of surplus canal water (due to rainfall, diminished draw-off for irrigation, or accidental excess admission at the headworks), so that the designed full-supply level of the canal may be preserved downstream of them and the danger of breaches may thus be avoided. When the canal has a sufficient number of aqueducts, separate escapes may be unnecessary for regulation purposes, as it may be practicable to provide in the parapets of the former the amount of spill-way wanted (Fig. 68, p. **294*a***). If, however, the foundation of an aqueduct would thereby be damaged, an escape should be constructed instead upstream of that work, which should then have its parapets raised a little above full-supply to prevent spill over them. In the latter case escapes are of use for the removal of silt—for this purpose they should be pierced by sluice vents closed by shutters ; such vents should always be provided when the escapes have to act as level crossings. To get rid of a light deposit of silt the canal in flow should be stirred up by harrows, etc., the escapes should have their vents opened, and the muddy discharge passed out thereat. Escapes should be located where the discharge from them will not cause injury to lower lands, e.g. where the canal crosses a natural drainage line. They should also be constructed above a weak or dangerous part of the canal, such as a high embankment, so that the water level there may be reduced when necessary. The discharging power of an escape is somewhat less than that of a weir under otherwise similar conditions, for the former is parallel to the line of the flow, and thus discharges under a head continuously diminishing towards its downstream end, whereas the latter is at right angles to the current, and discharges with a uniform depth throughout its length. To allow for this effect the length of an escape should be increased slightly beyond that calculated as sufficient for a weir, or the discharging capacity of the former taken as somewhat less than that of the latter.

An escape on a non-alluvial canal in regard to its flood-discharging capacity is a cross-drainage work, and resembles a level crossing of an alluvial canal (Art. 230 (*a*)), but is a less elaborate design, as a regulator across the canal downstream is not provided in connection with it.

(*b*) *Single-Bank Canals.*—In single-bank canals escapes are the usual type of cross-drainage work. They are constructed across the streams traversed by the canals, and also upstream of weak points (such as long and high embankments), in order that they may prevent the canal from rising high there, or, in case of necessity, may allow it to be emptied quickly. They consist of weir walls of lengths sufficient to discharge the floods with a small depth over their crests (Fig. 66). That depth should, as a rule, not exceed 3 feet, as the canal embankment upstream and downstream of the escape will have to be raised correspondingly, and possibly for a considerable length, to prevent its being breached during floods.

The ends of the escapes are constructed as flanks raised at least to a foot above high-flood level; these run into the canal embankment for some distance on each side so as to form water-tight connections with it.

In the overfall length of the escape should be one or more sluice vents for scouring and unwatering purposes. The maximum width of each of these should not exceed 3 feet, so that they may easily be closed, and their sills should be about 6 inches below canal bed, so as to increase their scouring power. As these vents are apt to leak, it is best to cut in them double sluice board grooves 1 foot or 15 inches apart. Into these grooves double sets of 3-inch planks can be inserted during the fair weather, and the intermediate space can then be filled with clay to make a water-tight stopping. During the flood season only one set of planks without any clay stopping should be used, so that the vents may be opened quickly when necessary to assist in discharging floods. Great care should be taken that the tail channels below all escapes are always maintained free from obstructions to flow. Quick-acting devices for the release of the sluice boards are practically never used on these canals, as they are of so small and unimportant a size.

A design for a pitched slope escape is described in Article 131.

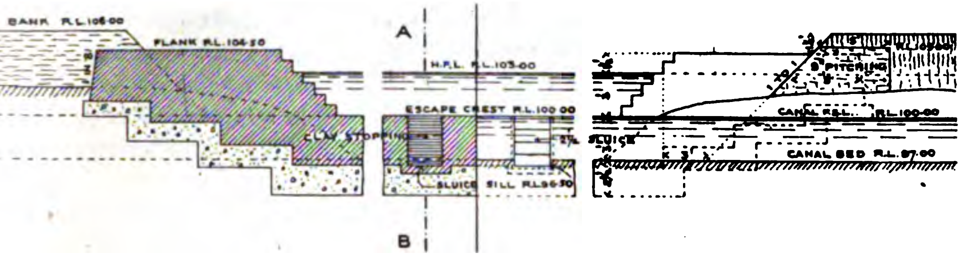
148. Natural Escapes.

Natural escapes are simple channels excavated on the downstream side of the canal and at right angles to it, so that they may act as safety valves, and reduce its surface level when that would otherwise rise unduly (Fig. 67). They should

FIG. 66

MASONRY ESCAPE

HALF LONGITUDINAL SECTION HALF ELEVATION



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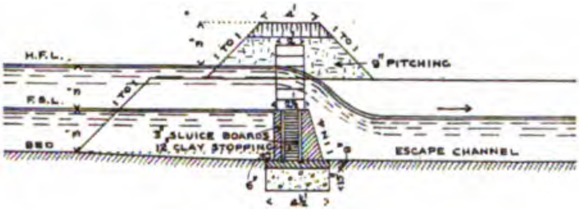
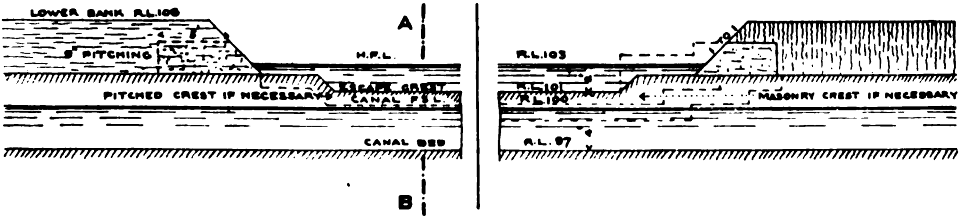


FIG. 67

NATURAL ESCAPE

HALF LONGITUDINAL SECTION HALF ELEVATION



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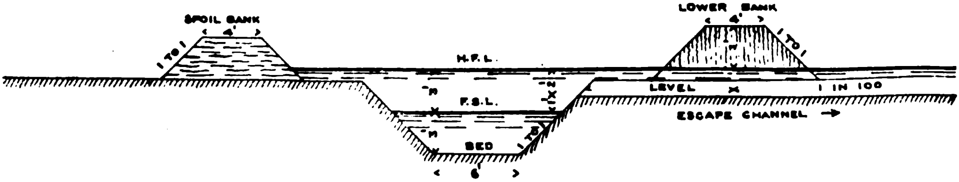


be located at places where the ground at and below the required sill level is hard and not easily erodible, and where the water discharged by them will not injure lower lands. For this latter purpose it is best that they should be formed near cross-drainages into which the spill from them can soon pass. To prevent scour channels forming down them when the ground is somewhat soft, all that is necessary is to build across them in the centre line of the canal embankment a small bar of concrete or masonry with raised flanks, or to pitch their beds for a length of a few feet.

The crest level of such escapes should be about 2 feet below the high-flood level of single-bank canals, and about 6 inches above the full-supply level of double-bank canals. In the former case they will thus never be subjected to a great depth of overflow, and to a large amount of scour, nor will they be called into action except during intense floods. In the latter they will allow, without overflowing, of a moderate increase of the canal's full-supply discharge when that becomes necessary; by its design such a canal is not liable to have its level increased by cross-drainage.

149. Tail Escape.

The end of the canal should be near a natural drainage line, and across it should be built a tail escape discharging into that drainage course. This will enable the canal to be maintained at full-supply level for the purposes of the tail distributary; it will also allow the canal to be drained dry when necessary, or will permit of surplus water being passed out of it without "wire-drawing" taking place.

"Wire-drawing" is the name given to the effect produced by a rapid increase to the bed fall, or to the surface slope of the water; the consequent greater velocity may cause the canal bed to be scoured and its full-supply level lowered for some distance. The scouring of the bed of the tail of a canal in soft soil would happen were its discharge allowed to pass direct, without the protection of a tail escape, into a cross-drainage channel at a lower level and with a steep inclination.

In design the tail escape will ordinarily be like that of a masonry escape (Art. 147 (*b*) and Fig. 66), and should have escape ventage equal to the waterway of the canal at its tail; the length of its overfall crest and height of its raised flanks should be sufficient to deal with any surplus discharge which may occur. It should, if possible, have good foundations; if the foundations are naturally insecure, they should be protected by stone pitching, or, in bad cases, by a water cushion, when the design will become somewhat similar to that of a vertical fall (Art. 144 and Fig. 64, p. 282).

B. CROSS-DRAINAGE WORKS.

150. High-Flood Discharging Capacity.

Before any cross-drainage work can be properly designed, it is necessary to determine what is the maximum amount of flow it may be called upon to pass, for it must be able to discharge safely the greatest flood as it arrives, seeing that there is practically no reservoir flood-absorptive capacity in the channel of an ordinary stream. The determination of high-flood discharges has been discussed in Article 52. It will not suffice to provide a waterway only just sufficient to pass the flood, as this will not allow any margin for an abnormal high discharge greater than that calculated upon, nor will it provide for the passage of bushes, trees, etc., which may be borne down by the flood. There is also the chance that the stream bed may have silted up, and thus contracted the area of the waterway. For these reasons, when designing cross-drainage works, a clear headway of at least 1 foot should be allowed for above the calculated high-flood level in the case of very small streams, and this safety margin should be made greater with the increase in size of the drainage up to 6 feet in the case of large rivers or streams liable to heavy discharge, owing to the nature and situation of their catchments. Arched structures have more headway structurally than others, but this increase of headway may be necessary to permit of the safe passage of trees and bushes through the vents.

Certain engineers hold that the blocking effect of the silt sometimes left after small freshets under the beds of cross-drainage works may be neglected, as the deposit will rapidly be scoured away by a heavy flood. This, no doubt, is eventually true, but the scouring action will require some time to be effectual, and, until it is completed, the waterway will be contracted and the safety of the work endangered. Again, they hold that the cross-section of cross-drainage works is generally so massive that it can easily resist some heading up of the flood. This also is partly true, but an obstructed stream bearing trees and bushes may thereby be dammed up so high as seriously to imperil the stability of a work, and even large aqueducts have thus been carried away. To increase the discharging capacity of certain arched waterways, they have been built with trumpet-shaped entrances and exits; this is rather a refinement, and is, anyhow, difficult of execution—it is far safer to have a plain, unobstructed waterway of full extent.

Some streams with gentle longitudinal slopes and carrying heavy sand have been known to silt up to the springing level of the cross-drainage works on them. If this result is likely to happen, care should be taken to cross the stream at a comparatively high level, so as to induce greater scouring power. The height to springing from bed level of a work on such a stream of any size should never be less than 6 feet, and may with advantage not be less than 10 feet; this will have the further benefit that it will allow traffic to pass under the canal.

It must be remembered that the destruction of, or extensive damage to, a cross-drainage work may involve an expensive repair, which may take long to complete, and thus a large area of irrigated crops downstream of the work may suffer. All reasonable precautions should therefore be taken to obviate it, and the principal of these is the provision of ample flood waterway.

The marking permanently on a cross-drainage work of its flood record has been described in Article 29 (*a*).

151. Alignment of Cross-Drainage Works.

In order that a cross-drainage work may have the most effective flood-discharging power, it should cross the stream at right angles, and the stream should approach and leave it with a straight course for a considerable length. For a small stream with quick flow this length on the upstream side of the work should not be less than ten times the bed-width of the stream, and for a large one with slow flow, not less than five times its bed-width; on the downstream side the distances should be doubled.

Should the stream have a tortuous course, it should be straightened, and should its general direction be oblique to the cross-drainage work, it may be necessary to cut a right-angled diversion for it. An oblique approach to the cross-drainage work will cause its piers and abutments to offer considerable obstruction to flow and to produce eddying motion, which will still further diminish its discharging power, and may cause silting. The bed of the stream within the above limits should, as much as practicable, be freed from obstructions, and its waterway be made as nearly as possible of an even and regular cross-section. The spoil thus excavated, if of suitable character, can be utilised in the formation of the approach embankments of the canal.

The site chosen for the crossing of a stream should preferably be one favourable to the construction of the cross-drainage work on it, i.e. the foundations should be of an unscourable character, and the natural banks hard and high, so as to diminish the cost of the wing walls and canal embankment. The selection of the sites will thus often have a considerable influence on the alignment of the whole canal. As the works are costly, their number should be reduced as far as may be, i.e. when possible, two streams should be crossed together below their confluence instead of separately above it, and thus one set of wing walls will be saved. It is, moreover, not advisable to cross streams just above their junction, as then each may block the other in high flood, and raise its level abnormally upstream of the cross-drainage work; this is particularly important when the stream crossed is a tributary of a much larger one. Where economically practicable, minor streams may be diverted some little distance upstream of the canal into the major ones.

152. Details of Masonry Cross-Drainage Works.

(*a*) *Foundations.*—See Article 37.

(*b*) *Wing Walls.*—See Articles 38 and 39.

(*c*) *Staunching Walls and Forks.*—See Article 40.

(*d*) *Batters of Walls.*—To ensure that the junction of the earthwork will always remain in water-tight connection with the masonry of cross-drainage works, it is necessary that the interior faces of all abutting walls should be built with batters; for convenience of setting out in construction the best ordinary batters are 3, 2, 1½, and 1 inches to the foot. Similarly, excavations for the building of walls should be given a slight side slope down to the top of the foundations, and the spaces thus formed should be carefully filled with water-tight soil. The object of these arrangements is to secure that during and after settlement the earthwork will be compressed tightly against the masonry and the side of the excavation. Stepped faces tend to cause settlement cracks, as the earthwork over the steps is likely to lodge on them while the adjacent embankment settles independently.

(*e*) *Piers.*—High piers should be given a small batter, say, of ½ inch to the foot, to gain greater stability and a better appearance (Fig. 68). If piers and abutments are massive and heavy, they may be lightened by being built cellular when the nature of the foundation requires such relief of weight.

The upstream end of the pier should be formed as a "cut-water"; in plan the best section for this is one made by striking each side as an arc of a circle, having its centre at the opposite face of the end of the pier proper. On the downstream side the pier should be ended with an "ease-water," which in plan may be a semicircle. For the sake of economy, both these ends of the pier may instead be built with straight sides, i.e. triangular in plan. The cut- and ease-waters should be finished off at the springing line by stone caps. By means of these ends the stream will be passed under the cross-drainage work with the most regular motion, and one free from eddies which would diminish its discharging power. On some canals it has been found that sharp-ended cut-waters catch and hold floating *débris*, and that it is therefore better to have semicircular ends to prevent such lodgment.

If there is a long series of arches, it should be split into short sections by "abutment piers," having a thickness at springing about half as much again as that of the ordinary piers and batters of about 1 in 6, so as to make them able, even when unsupported, to resist the thrust of only one abutting arch. These piers will thus prevent the failure of one of the arches from involving that of the whole series.

(*f*) *Dimensions of Arched Structures.*—The following table gives some leading dimensions which may be adopted with safety for canals of ordinary size, say, with full-supply depth of from 6 to 8 feet:

Items.	For Spans of—				
	10 Feet.	15 Feet.	20 Feet.	25 Feet.	30 Feet.
	Dimensions in Feet.				
1. Rise of arch	2	2½	3	3½	4½
2. Thickness of arch ring at crown ..	1	1¼	1½	1¾	2
3. Thickness of arch ring at springing ..	1¼	1½	1¾	2	2¼
4. Thickness of abutment at springing (rear batter 1 in 6)	3½	4	4½	5	6
5. Thickness of ordinary pier at springing (batters 1 in 24)	2½	2¾	3	3¼	3½
6. High-flood level below springing (assuming small spans will be adopted for small streams)	½	¾	1	1¼	1½

An empirical rule for the uniform thickness in inches of an arch ring is that it should be equal to the span in feet.

(*g*) *Waterproofing Cross-Drainage Vents.*—The outer surfaces of the masonry coverings of the vents of aqueducts, culverts, and slab drains should be some little depth below canal bed, partly to allow easily of the future deepening of the canal should that become necessary, and partly to secure a water-tight layer of concrete or puddled clay over the masonry coverings. If, however, the levels do not permit of forming such waterproofing, the tops of the joints of the masonry coverings should be laid in cement or gauged mortar so as to be water-tight.

(*h*) *Pitching of Canal Embankments.*—All embankments exposed to the rush of water at the wing walls of cross-drainage works, or to the lap of waves on flooded areas, should be securely pitched at least to 1 foot above the reach of the water, and the toes of banks on soft ground should be protected from erosion by rough rubble mounds formed of stone or insoluble *débris* from excavations, etc.

153. General Remarks on Cross-Drainage Works.

Cross-drainage works are of three main descriptions:

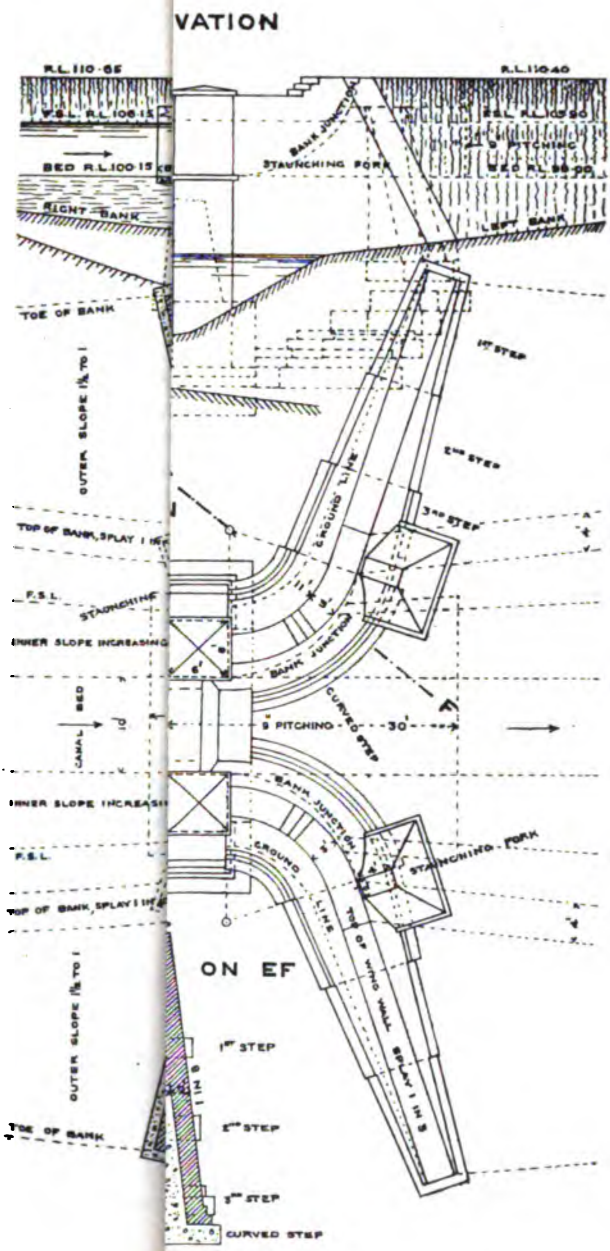
(i) Those leading the drainage under the canal, e.g., aqueducts, culverts, and slab drains;
(ii) Those passing the canal under the drainage, e.g., superpassages and siphons;
(iii) Those admitting the drainage into the canal, e.g., escapes (level crossings), intercepting weirs and reservoirs, and inlets.

The selection of one or other of these descriptions depends upon the relative levels of the high-flood level of the drainage and the bed level of the canal, and is usually determined by the general alignment of the canal. That alignment may, however, have to be altered in order to get a better type of cross-drainage work when the nature of the country permits of the change being made without greatly increased cost.

Class (i) has the advantage that the canal, which may be in flow throughout the year, is above ground, and can thus easily be maintained in working order. The works have the disadvantage that they are more susceptible, if badly designed or constructed, to flood damages, such as by scour of their foundations, by silting of the beds of the waterways, or by blocking of these by trees, etc., carried down. Destructive floods, however, occur but rarely, and time may be afforded to make good the damage sustained, which will usually be in the open, and thus more easily repairable than if it were underground. Damage should, of course, be prevented by proper design and construction.

Class (ii) has the advantage that floods are more likely to injure the canal earthworks than the cross-drainage work, and the damage may be more easily made good than in the case of Class (i). However, repaired earthwork may subsequently give more trouble from leakage, etc., than repaired masonry. The disadvantage of this class lies in the maintenance of the canal, which will be underground, and may be in flow throughout the year, as difficulty may be caused by silt deposit, etc. On the whole it may be said that works of class (i) are superior to those of class (ii).

Class (iii) works are decidedly inferior to the other two classes, especially if they admit silty flood water directly into the canal, as this will increase the work and cost of maintenance. An intercepting reservoir is in this connection the best of this class, as it is likely to impound most of the silt for many years, and to intercept all the heavier detritus. In respect to this class the canal must be made capable of dealing with the flood level due to the temporary admission into it of the drainage. The great objections to class (iii) works are the danger they involve to the canal and the expense due to the necessity for the employment of special men to attend to their regulation during the flood season.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R.L.110·40
F.S.L. R.L.106·15
F.S.L. R.L.103·90
BED R.L.100·15
BED R.L.98·00
9" PITCHING
BANK JUNCTION
STAUNCHING FORK
RIGHT BANK
LEFT BANK
TOE OF BANK
OUTER SLOPE 1½ TO 1
1st STEP
2nd STEP
3rd STEP
GROUND LINE
TOP OF BANK, SPLAY 1 IN
F.S.L.
STAUNCHING
INNER SLOPE INCREASING
CANAL BED
10'
6'
8'
E
F
CURVED STEP
9" PITCHING
30'
BANK JUNCTION
STAUNCHING FORK
GROUND LINE
TOP OF WING WALL SPLAY 1 IN 5
ON EF
1 IN 8
CURVED STEP

154. Aqueducts.

(*a*) *Classification.*—Aqueducts are structures for carrying a canal over large streams or considerable depressions in its course. They may be:

Masonry Aqueducts;
Trough Aqueducts of iron or wood; or
Pipe Aqueducts.

(*b*) *Masonry Aqueducts* (Fig. 68).—These are built with arches, are the most durable and handsome type, and require the least expenditure on maintenance. In new countries they are often expensive to construct; in America, where wooden trough aqueducts were formerly built, it is, however, now becoming recognised that the greater expense of masonry structures is justified by their increased permanence and reliability. In India aqueducts are almost invariably built in brickwork or masonry. To reduce the cost, the arches may be of plain or reinforced concrete, but such arches will be more difficult to construct securely and water-tight and will not look so well. Moreover, sufficient experience has not yet been gained of the effect of constant saturation by air-charged moving water on reinforced structures.

The bed of the aqueduct should be a little lower than that of the canal near it, so as to work in with any deepening of the latter which may afterwards be found necessary (Art. 109 (*a*)). The parapet walls (or at least the upstream one) should be 6 inches higher than canal full-supply, to enable somewhat larger discharges to be passed down when necessary, and to provide for the expansion of the canal; if the top of the downstream one is lowered to full-supply level, it can be raised temporarily by sods, although this is hardly a satisfactory arrangement. In the downstream parapet may be one or more scouring sluices, with sill at aqueduct bed level for silt removal when required. This parapet, or a part of its length, may be utilised as an overflow escape for the discharge of surplus canal water, in which case the one opposite would be raised a few inches higher than it.

It will generally be found best to limit the span to 30 feet, except in the case of a very high aqueduct, where the extra rise of a wide arch can be allowed. Also it is desirable, as far as possible, to have spans of the same size for all similar works on a canal in order that their centres may be utilised for the construction of one after another.

(*c*) *Trough Aqueducts* (Fig. 69).—In these the canal is led in a trough formed of mild steel, iron, or wood, which will usually be carried on framed standards of the same material; as these materials, if unprotected, are perishable under the action of sun and water, they should be kept well painted or tarred; wooden troughs generally crack when dry under the action of the sun, and are thus rarely water-tight. If the troughs are formed with lap joints to secure water-tightness, the overlaps should be on the downstream side, so that the quick-flowing water may pass smoothly over them; if they are on the upstream side, waves will be produced by the projections, and spill over the edge of the trough may take place. For cheapness and facility of erection, it will probably be found that 20 feet is the best span to adopt. The figure shows the verticals of the standards each made in two portable lengths bolted together during erection.

An advantage of a trough over an arched aqueduct is that it can be used when the headway is restricted, i.e. when the height between the high-flood level of the stream and the bed of the canal is small. It is also the cheapest form of structure when the canal has to be carried over a deep depression; there are several long and high trough aqueducts in America.

The abutment can be formed, either by continuing the trough well into the embankment of the canal, and by supporting its end by a standard, or by building it at the stream flank in masonry. The latter arrangement is the more lasting of the two alternatives, and permits of a more staunch connection with the canal embankment. Special arrangements should be made for securing a water-tight connection between the trough and the masonry, which will allow for the expansion and contraction of the metal, although these will not be great if the canal is maintained in constant flow. One method of making an elastic joint is shown in Fig. 69; at the end of the trough is fixed lead sheeting along its bed and sides, and this is fitted into a corresponding groove formed in the abutment, which thereafter is filled with a composition of gas tar, pitch, and fine sand poured in hot. Another precaution which has been taken in addition is to insert in a recess in the bed-stone capping the abutment, and 4 inches from the end and

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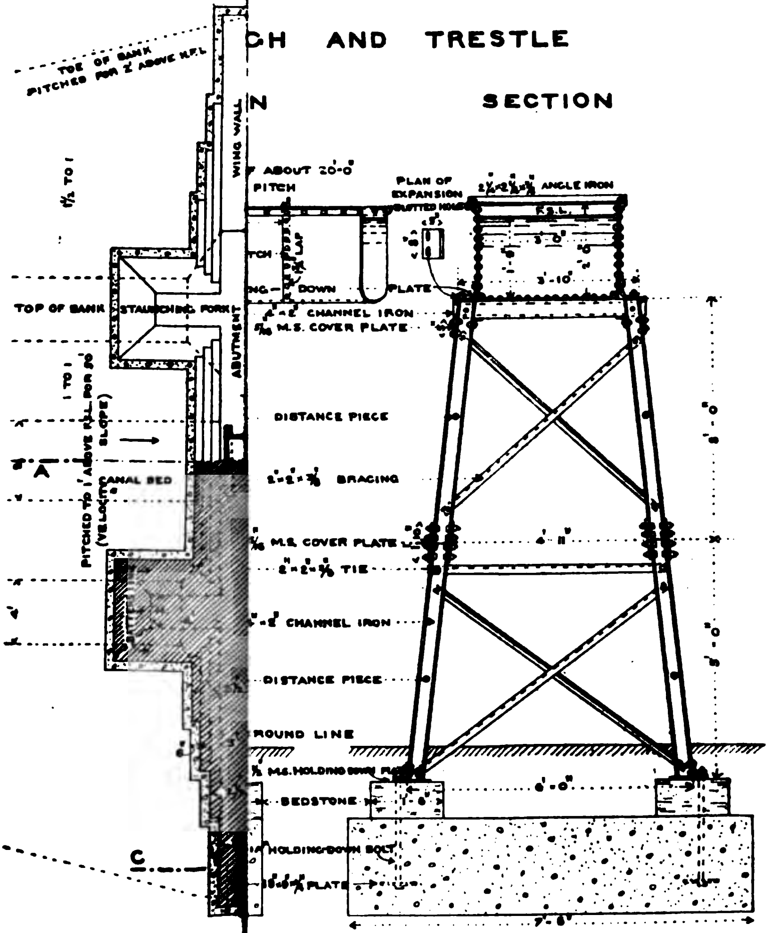

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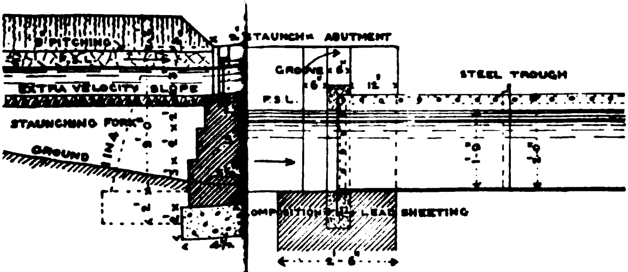

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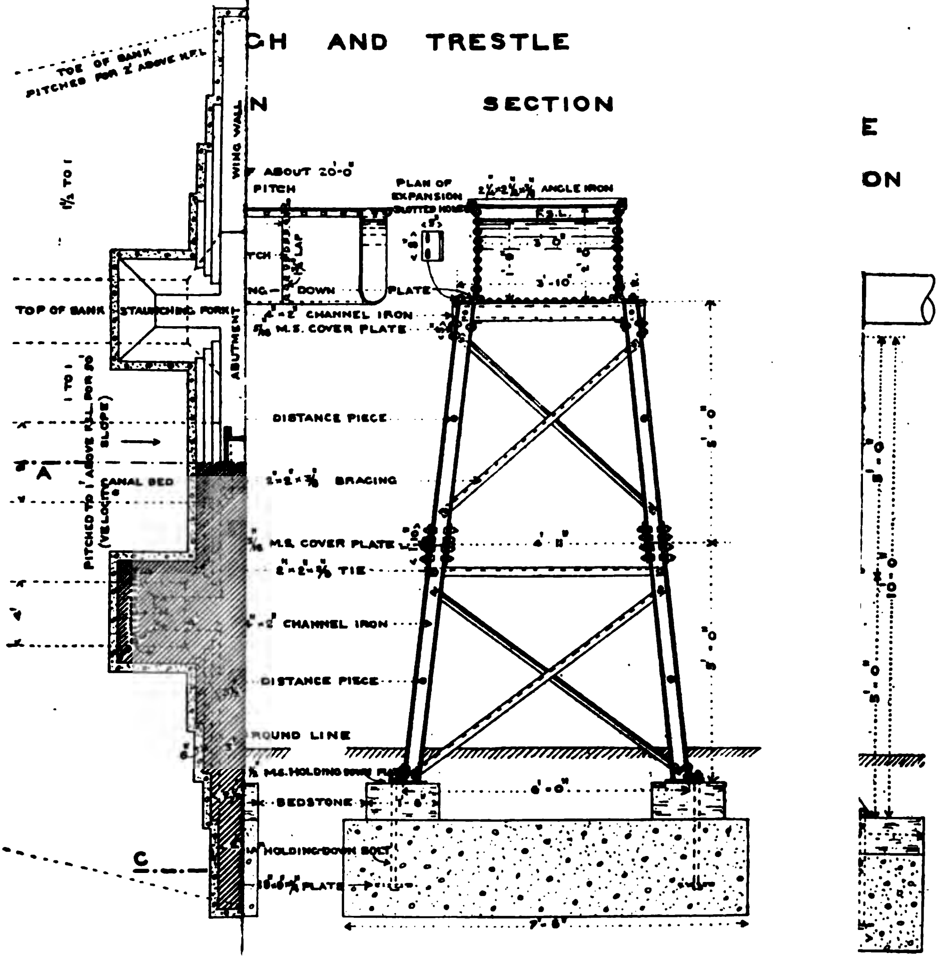
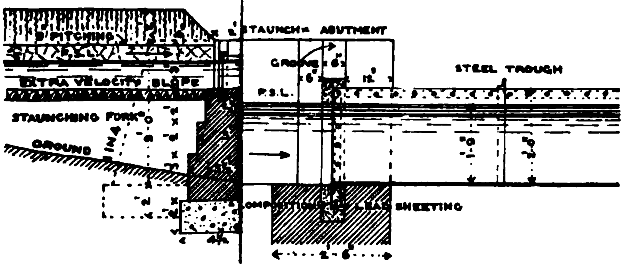


AIL OF WATER-TIGHT JOINT

JT

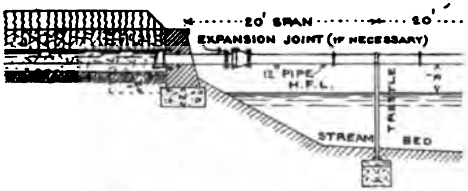


ROUT

FIG. 70

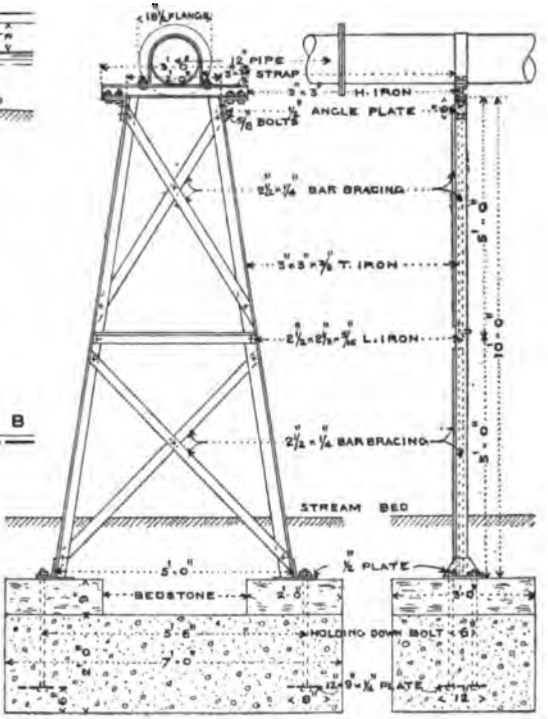
PIPE AQUEDUCT

SECTION ON AB

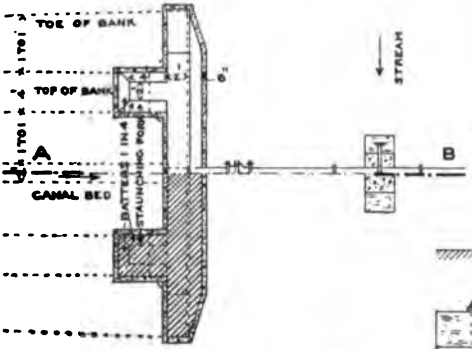


DETAIL OF TRESTLE

SECTION ELEVATION

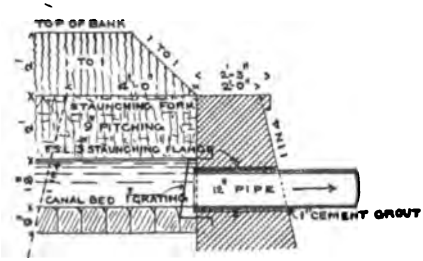


PART FINISHED PLAN

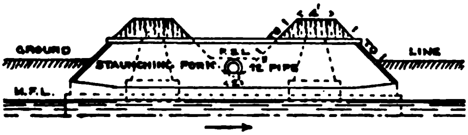


PART FOUNDATION PLAN

DETAIL OF ABUTMENT JOINT



ELEVATION OF ABUTMENT



under the entire bed of the trough a 9-inch wide pillow of felt soaked in tallow, so as to make a water-tight bearing joint.

For both classes (*b*) and (*c*) the canal waterway should be reduced as much as possible in order to lessen the expense of construction. The reduction must, of course, be accompanied by a corresponding increase of the velocity of the canal flow (Art. 115 (*b*)), and that will have to be effected by increasing locally the longitudinal slope of the canal. This will somewhat decrease the area under command, but the loss can, in most cases, be made up by a short extension of the canal.

(*d*) *Pipe Aqueducts* (Fig. 70).—These can be adopted only when the canal discharge is small. As their name implies, they are formed of pipes through which the canal supply flows. The pipes are carried across the stream from one abutment to the other, without supports if the length is short, or are supported by intermediate piers or standards if that exceeds two or three lengths of pipe. By arranging for a vertical drop in the canal at the head of the aqueduct, and thus gaining pressure, the pipe can be made to pass a large discharge compared with its cross-sectional area.

155. **Culverts** (FIG. 71).

Culverts differ from aqueducts in that they pass under the canal embankments which are carried continuously over them (so that they are not visible from the top), and are not between the ends of flank embankments. They are suitable for providing passages under the canal for streams smaller than those for which aqueducts are necessary. As they have to carry the weight of the embankments, it is advisable not to make them of spans greater than 10 feet, but ones up to 25 feet have been built.

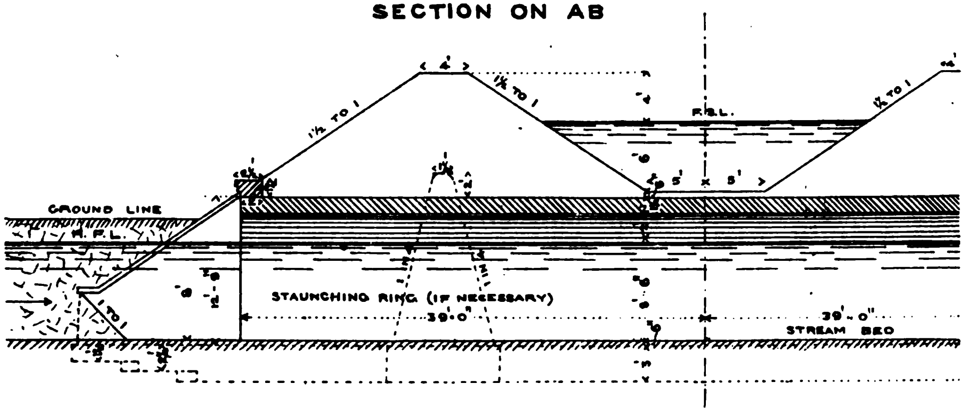
If the canal bed is less than 2 feet above the top of the culvert arch, and the embankment is made of porous material, it may be necessary, in order to prevent leakage along the extrados, to build staunching rings round the culvert under the centre lines of the canal banks; these rings should project at least 2 feet into the earthwork.

When the valley crossed is deeper than is necessary to provide flood waterway, and there are sound foundations available up one of its sides, economy can be effected by constructing the culvert, not over the stream bed, but some distance

FIG. 71

CULVERT

SECTION ON AB



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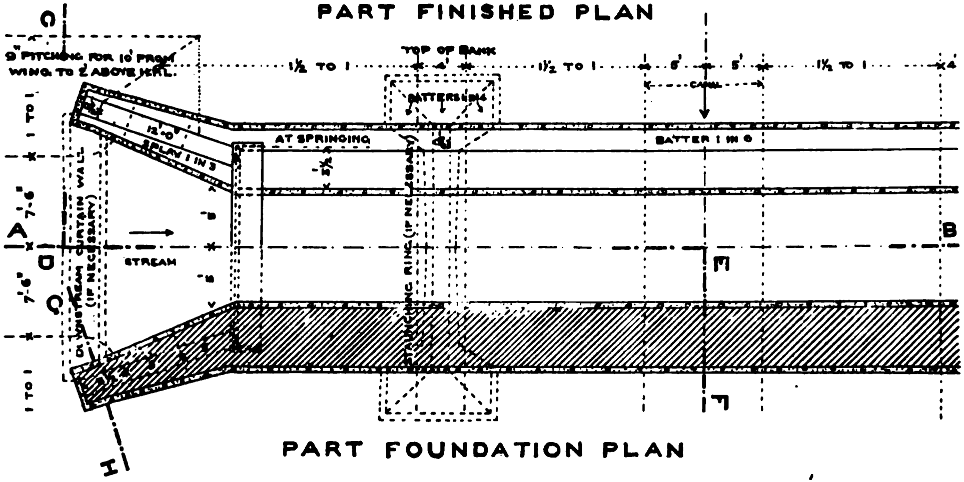
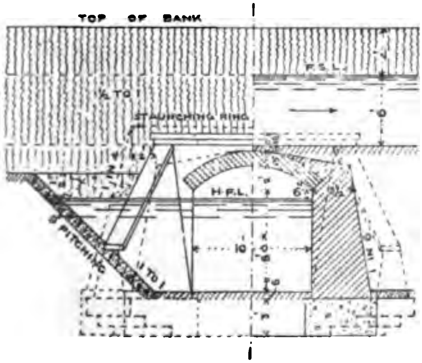
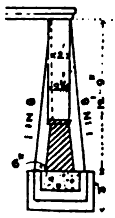


PART FOUNDATION PLAN

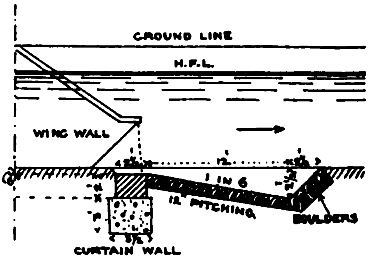
SECTION ON CDEF



SECTION ON GH



TAIL PROTECTION FOR BAD FOUNDATIONS



up that side. The canal embankment has, anyhow, to be carried across the valley, but if this plan is adopted, a shorter, cheaper culvert will result. The embankment will thus during floods impound water below culvert high-flood level and for some time below culvert sill level; its base will therefore have to be carefully constructed water-tight, but, anyhow, on account of its height, this ought to be done.

156. Slab Drains (FIG. 72).

Slab drains are suitable for crossing only very small streams. Their span will be limited by the length of the slabs available, but can be increased by about a foot by corbelling out from the top of the piers and abutments. Even with this device it is better not to have a span of a total width greater than 4 feet.

The advantage of a slab drain over a culvert consists in the fact that it can be built where, on account of the levels, the available height between the bed of the canal and the high-flood level of the stream is small. This advantage is not a great one, as there should always be a safety margin between the latter and the intrados of the work; this, as a rule, will not be less than one-third the rise of the arch of the culvert above high-flood level, but the slab drain will have a wider waterway at the top level.

The disadvantage of a slab drain with many vents lies in the number of the piers which will obstruct the flow of the stream, and may cause it to silt up its bed and may catch *débris* which will block the waterway. Slab drains are thus generally not suitable for crossing large streams nor those which carry much silt and *débris*.

157. Superpassages.

(*a*) *General Remarks*.—Superpassages may be defined as works which carry canals under cross-drainages; they are of two main descriptions, namely, those in which—

(i) The canal is led with a continuous falling gradient under the cross-drainage;

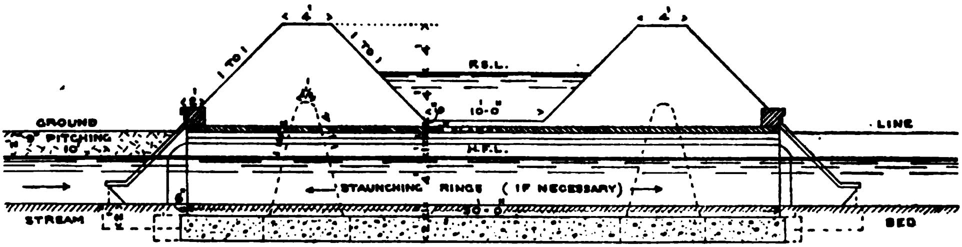
(ii) The canal is made to dip under the cross-drainage and to rise again after that has been passed.

The objections to a superpassage are the expense of crossing a large shallow stream waterway, and in the case of (ii) the

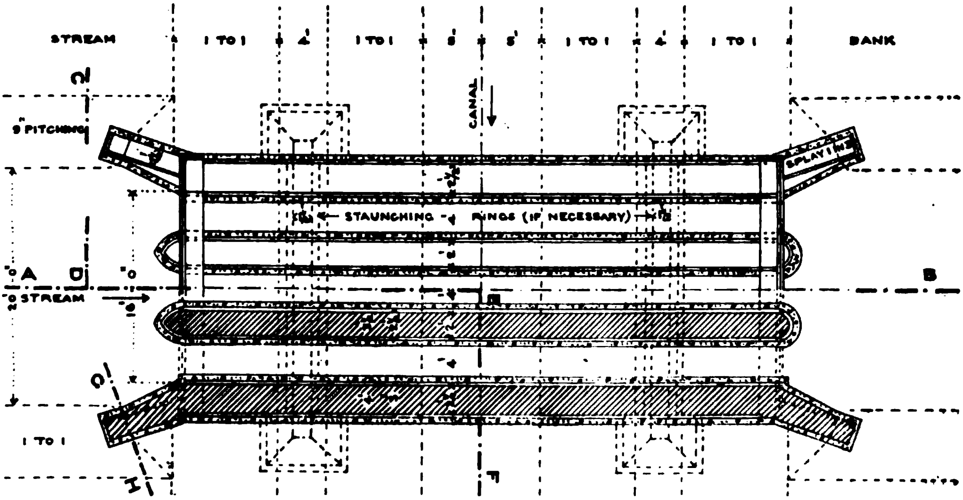
FIG. 72

SLAB DRAIN

SECTION ON AB

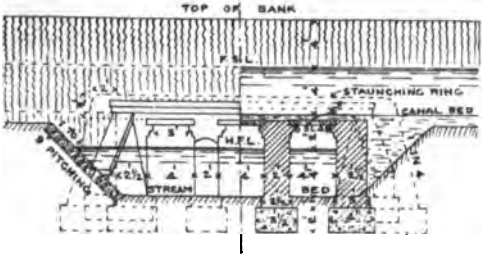


HALF FINISHED PLAN

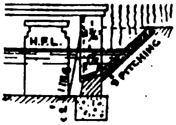


HALF FOUNDATION PLAN

SECTION ON CDEF



SECTION ON GH



liability of the canal to silt in the work. To meet these the canal has its velocity increased at the crossing so as to reduce its waterway through the structure, and so as to give it scouring capacity ; this involves a loss of head, and thus a loss of command. Another objection is that the parapets of the superpassage have to be raised sufficiently to contain an abnormal flood, for if that overtopped them, a breach of the canal would probably result. In the case of an aqueduct such a flood would be less likely to cause damage, as only a small amount of heading up upstream would greatly increase the discharging capacity of the work. The main advantage of a superpassage is that, like an aqueduct, it prevents the entry of flood water and silt into the canal ; it is thus superior to an escape or level crossing, as it is automatic, and does not require a maintenance gang to supervise its working (Art. 153, Class (iii)). A further advantage is that when the cross-drainage is not flowing its bed may be used as a surface roadway for traffic crossing the canal line.

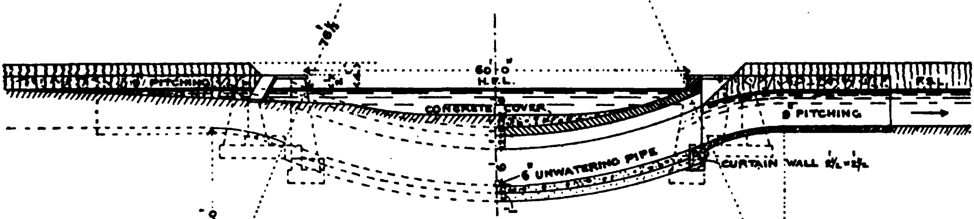
(*b*) *Class* (*i*) *Superpassages.*—In this class the level of the canal bed is so much below that of the cross-drainage that the former can be passed with its continuous falling gradient below the latter. The work is thus like an aqueduct reversed, and the canal has no tendency to silt up in it. Another advantage of this class is that the canal water has no upward bursting effect on its arched roof. It is not advisable much to raise the bed of the cross-drainage to enable the canal to go under it, as this will check the velocity of floods and cause them to silt the bed upstream, which will probably produce still further silting, and thus may considerably heighten the flood level of the stream.

(*c*) *Class* (*ii*) *Superpassages.*—In this class the bed of the canal is at the same level as that of the cross-drainage, or only slightly below it. In longitudinal section the superpassage can be made either curved (Fig. 73), or rectangular, or with sloped approaches (similar to Fig. 74, but as there drawn with the canal and stream transposed). The curved form is difficult to construct, but is less destructive to the flow of the canal, and thus has less tendency to silt up ; further, it assists the resistance of the cover of the canal waterway to bursting pressure by transmitting part of that to the abutments, and thus utilises their weight. The rectangular form is best adapted to a canal having a clear flow, as it checks down-

FIG. 73

SUPERPASSAGE

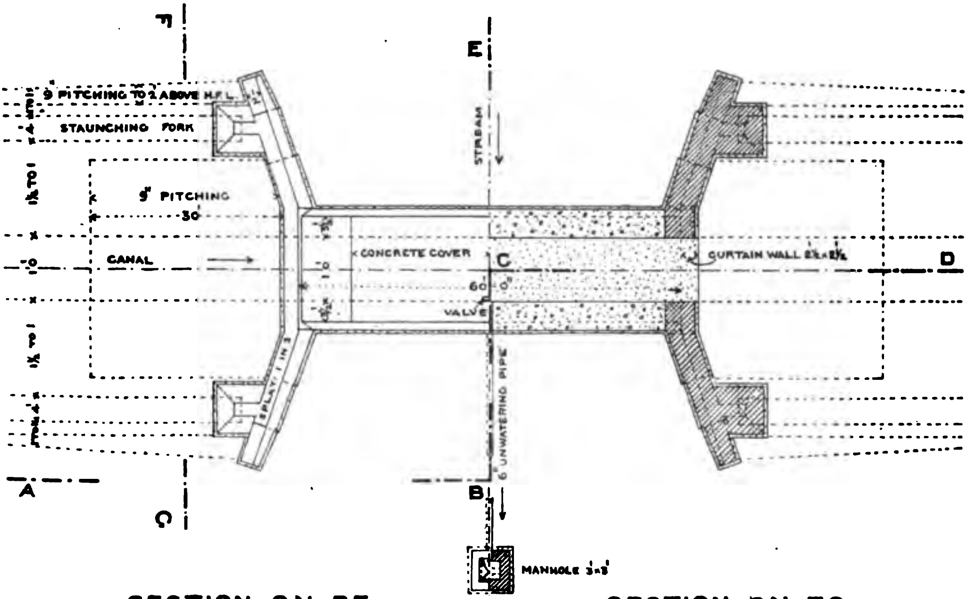
SECTION ON ABCD



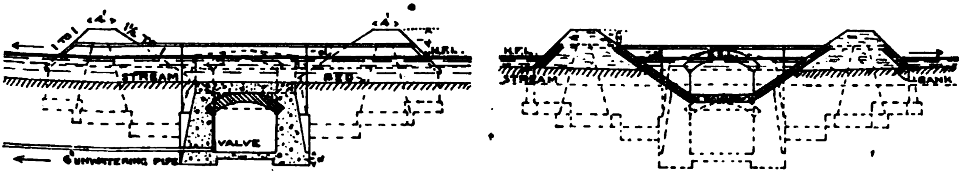
NOTE

ARCH — SPAN, 10'; RISE, 2'; RING 1½' THICK.
ABUTMENT — AT SPRINGING 3½' THICK; REAR BATTER, 1 IN 6; HT TO SPRINGING, 5'.
WING WALL — TOP WIDTH, 2'; FRONT BATTER, 1 IN 6; REAR, VERTICAL.
STAUNCHING FORK — PROJECTION, 4'; TOP WIDTH, 2'; BATTERS, 1 IN 4.

HALF FINISHED PLAN HALF FOUNDATION PLAN



SECTION ON BE SECTION ON FG



stream the extra velocity given through the work, and thus with a turbid flow might cause silting there; it, moreover, has the advantage that it obviates the necessity for much protection to the bed and sides of the canal downstream. The form with sloped approaches is most suited to a canal having a muddy flow, for it lessens the tendency to the silting up of the interior waterway of the superpassage, as the extra velocity given is maintained through it; for this reason protection by pitching of the canal bed and sides downstream is necessary until the ordinary velocity is resumed.

To assist in unwatering the superpassage when required, a drain pipe controlled by a valve might be led from the centre of its canal bed out into the cross-drainage bed downstream. If a free outfall can be given to the pipe within a short distance, so much the better, but if this is not practicable, the pipe can end in a covered manhole from which the contents of the bottom of the superpassage can be pumped out after the greater volume of the water at the top has flowed away by gravitation.

It is, of course, essential that the roof of the superpassage should be sufficiently strong to withstand the bursting pressure of the canal water when there is not any stream flood water over it, which will generally be the case. To provide against such an accident, it is usual to make the thickness of the roof four-tenths or even one-half of the head of the canal upstream of the work. To prevent that head increasing unduly, an escape should be provided on the upstream side of the work, either in its downstream wing wall, or in the canal near to it. The end and wing walls have to be raised well above the flood level of the drainage, so as not to allow floods to spill into the canal.

158. Siphons.

A siphon should strictly be called an inverted siphon, as it dips below the general level instead of rising above it. It may be defined as a work which carries a canal under a drainage, having its bed level much below that of the general canal. The bursting pressure at the lower parts of the siphon is thus so considerable that it can be resisted only by forming it either as a metallic or reinforced pipe at great cost. This class of work is therefore ordinarily possible economically only for conveying small volumes of water, as for a town water supply, and is usually too costly for the large ones of an irrigation canal, but several examples of large irrigation siphons have been built. Possibly it may be found cheaper thus to cross a ravine than by an aqueduct or by a diversion of the canal upstream to where the bed of the drainage is at a much higher level. Another disadvantage of this class of work is the loss of head it entails to overcome the friction of a long length of pipe. In a siphon a canal is given a high velocity, partly to reduce the area and cost of its waterway, and partly to enable it to scour itself free fron silt ; this also entails loss of head. (See also Art. 229 (*b*).)

159. Siphon Aqueducts (Fig. 74).

A siphon aqueduct is often called a siphon, although it has practically a free flow (and that an inverted one), as it dips only a little below the general level. It may be defined as a work which carries a drainage under a canal when the two have similar bed levels ; it is thus the reverse of a superpassage of class (ii) (Art. 157 (*c*)). It is inferior to the latter work as it has to pass silty flood water, which may have a large volume and carry down large detritus, bushes, etc. It is therefore not a suitable design for a stream bringing down boulders, large gravel, or trees.

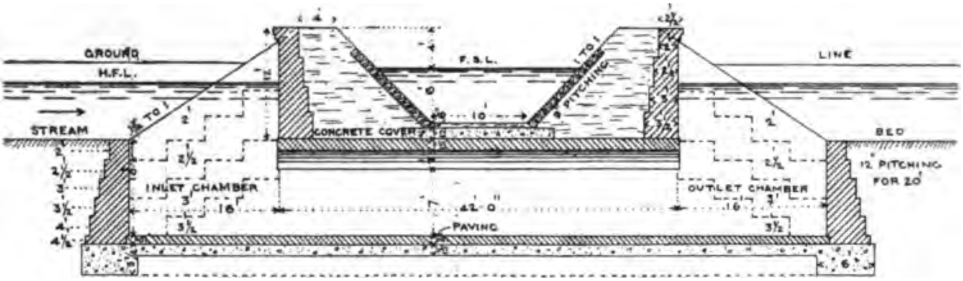
To diminish greatly the cross-sectional area of the vents of a siphon aqueduct and to obtain scouring power, the drainage water should have a considerable velocity through them, say, from 5 to 8 feet a second, but this will consume an amount of head which may not be available. To aid in producing and maintaining that velocity, the entrance to and exit from a work having to pass heavily-charged silty water should not be formed as vertical drops, but with gentle inclines, and should be wide rather than narrow, so that the vents should correspondingly be shallow, not deep. This has the further advantage that it lessens the depth of the excavation of the work which will result in considerable economy if either rock or springs are met at a high level.

Superpassages, siphons, and siphon aqueducts are not desirable works to have ; they should be designed only when superior cross-drainage works cannot be constructed on account of the adverse natural conditions of the levels of the canal and the streams crossed, and the flatness of the country not permitting a deviation of the canal to obtain more headway in

FIG. 74

SIPHON AQUEDUCT

SECTION ON AB



HALF FOUNDATION PLAN

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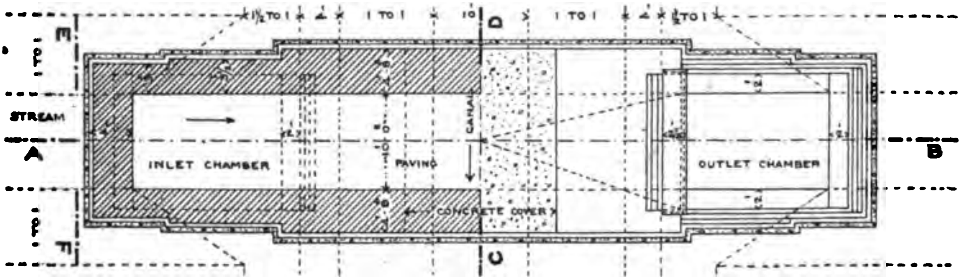

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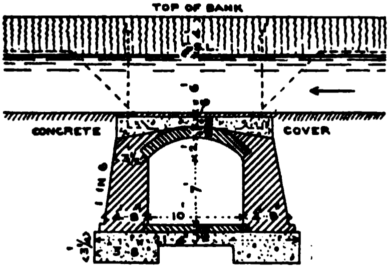

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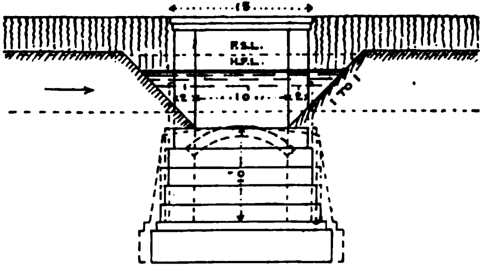
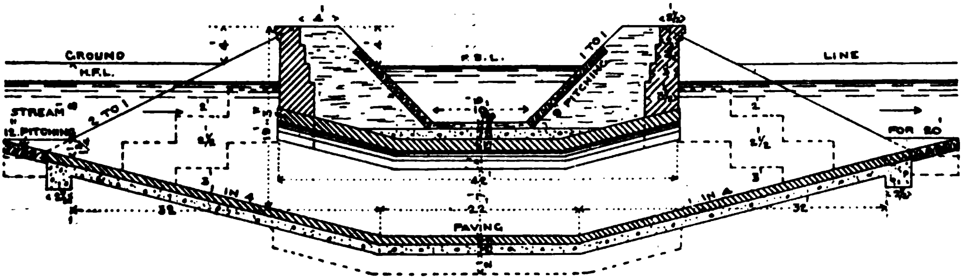


SECTION WITH SLOPED APPROACHES



the case of the first and last of these works, and because of the low elevation of the cross-drainage in that of the second one.

160. Interception of Long-Continued Cross-Drainage Flow.

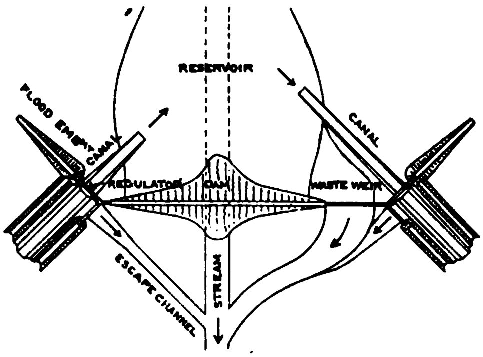
(*a*) *General Remarks.*—If the canal crosses a stream having a small perennial or long-continued flow, it may be advisable to admit this into the canal to make up for its loss in transit or to increase its discharge. This can be done by constructing on the line of the canal—

(i) An impounding reservoir;
(ii) A pick-up weir; or,
(iii) A feed channel.

The first two kinds of works may also prove economical structures in dealing with the cross-drainage, although there is no long-continued flow to intercept and utilise.

FIG. 75

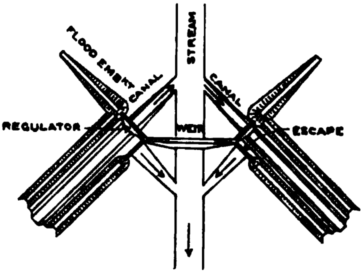
IMPOUNDING RESERVOIR



(*b*) *Impounding Reservoir* (Fig. 75).—Such a reservoir would be formed by throwing an earthen dam across the stream and by having on one or on each of both banks a waste weir to discharge the floods of the cross-drainage back into it downstream of the canal. The reservoir would for many years intercept heavy silt and stop it from entering the canal. To prevent its high flood raising the canal surface considerably, either long waste weirs should be provided, or shorter ones with regulators built across the canal both upstream and downstream of the work to block the rise, and with escapes constructed in continuation of them to pass off excess water flowing down or entering the canal. Where there is no long-continued fair-weather flow the objection to such a reservoir, if of any size, is that it will cause loss of water by evaporation and absorption, and will delay the passage of extra supply down the canal below it when the discharge has suddenly to be increased. If there is such flow, the first objection will not exist, but the second one will remain. An impounding reservoir, being on the canal itself, cannot well be utilised as a subsidiary reservoir for storing surplus canal flow unless it is constructed near the end of the canal, and thus becomes a tail reservoir (Art. 143).

FIG. 76

PICK-UP WEIR

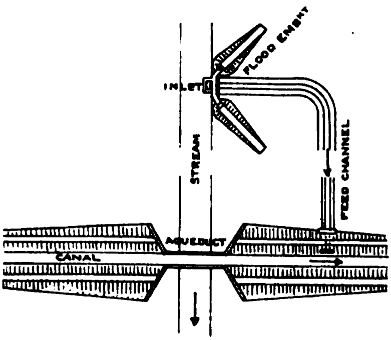


(c) *Pick-up Weir* (Fig. 76).—This would be built across the stream and have cross-regulators and escapes in continuation as in the case of (*b*); the flood depth should be reduced by making the weir long. Such a work would intercept heavy detritus from passing into the canal, but unless cross regulators are provided might admit heavy silt into it. With the cross regulators the design corresponds to a level crossing (Art. 230 (*a*)) on an alluvial canal.

(*d*) *Feed Channel* (Fig. 77).—If the stream crossed has a steep longitudinal fall upstream of the canal, and particularly if it has a waterfall or rapid above it, its long-continued flow can be passed by a supply channel excavated on one of its banks (preferably that downstream of the cross-drainage work) so as to tail into the canal. The channel would be shut off from floods by being led quickly into high ground, and by being protected with flood embankments where the ground is low, and would have a regulator with inlet chamber (or masonry bar across the stream) at its head. The canal itself would cross the stream by means of a cross-drainage work.

FIG. 77

FEED CHANNEL



(c) *Submerged Dam.*—This is a work designed to intercept a subterranean flow of water below a channel with a fissured or highly porous bed by opposing a water-tight barrier to its further passage underground. A trench is excavated through the water-bearing stratum and well into an impervious one, and either it is filled with puddle, or a water-tight masonry or concrete wall is constructed in it up to the level required for drawing off supply. If the country generally is of a porous water-charged nature, adits might be excavated on each flank and filled with porous material to lead subsoil flow to the submerged dam.

It is believed that there are few, if any, such works in India, but in America they are said to be frequent. In ordinary circumstances they must yield only a small amount of supply. The sites selected should be examined by means of trial pits, and, as a rule, will be where there is a natural underground water-tight bar and hard ground lies on the flanks of the channel. Probably the most abundant subsoil supplies are found in the dolomite formation ; in the Transvaal such bars are formed by natural faults, and discharges of as much as 60 cusecs are thus brought to the surface in areas which, superficially, are quite dry ; artificial development by submerged dams is there unnecessary, and might possibly defeat its object by causing the subterranean waters to take another course than that desired.

161. Catchwater Drains.

(*a*) *Catchwater Drains.*—Where a large amount of field drainage would pass into a single-bank canal, or be impounded by the upper embankment of a double-bank canal, catchwater drains are required to deal with it. To diminish their section and to prevent them from silting up, they should, whenever possible, be given a steeper fall than that of the canal.

They should not approach nearer than 10 feet from the upstream edge of a single-bank canal nor the outer toe of the upstream embankment of a double-banked canal, nor nearer than 5 feet from the borrow pits if these are excavated on that side of the canal. They should not be aligned very obliquely to the canal where the land is valuable, for if they did they would interfere with its cultivation and might entail increased expenditure on compensation. They should, when practicable, be led to the nearest cross-drainages and the beds of their outfalls into these should not be below the average high-flood level so that they may not be blocked frequently by the flood discharge of the streams. The ultimate development of a catchwater drain is when it diverts a minor stream to a major one (end of Art. 151), and thus saves the construction of a cross-drainage work for the former.

(*b*) *Pitched Inlet* (Fig. 78) *and Pipe Inlet or Superpassage* (Fig. 79).—If a catchwater drain cannot be led into a cross-drainage without greatly increasing its own length, size, and cost, its flow may be discharged into the canal at an inlet or be passed over it by a pipe superpassage. The inlet may be excavated as an open channel (pitched where the ground is soft) and having its outfall down the side slope of the canal, or may be formed of pipes 6 inches to 9 inches in diameter, protected at their head by a grating and catchpit, to prevent the entry of rubbish into the canal. A pipe inlet should preferably be located at a shallow depression, and should have a smaller rate of discharge than that probable from the catchment intercepted. The drainage will therefore at first pond up to a small depth against the canal embankment (which will be raised to contain it), and will drop its silt in the pool thus temporarily formed; the pipes will drain the impounded water gently into the canal, say, in the course of a day. Or the line of pipes may be continued and carried across the canal so as to form a superpassage. The pipes

FIG. 78

PITCHED INLET

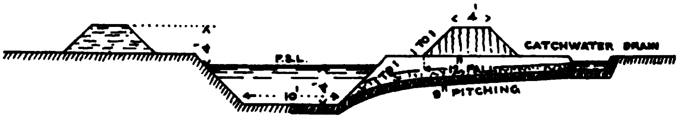
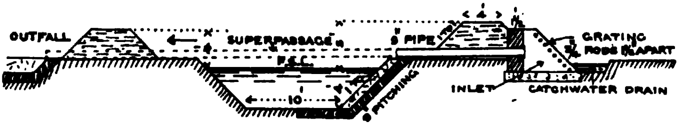


FIG. 79

PIPE INLET (OR SUPERPASSAGE)



should be at least 1 foot above canal full-supply level, should extend at least 2 feet beyond the downstream bank, and should discharge into a small cut (pitched, if necessary), and thence into a minor cross-drainage channel or over the land downstream. The superpassage should be located where its concentrated flow will not damage that land ; if such injury is likely to occur, it will be best to avoid it by passing the drainage into the canal by an inlet.

CHAPTER XII.

PHYSICS OF LARGE INDIAN RIVERS IN ALLUVIAL SOIL.

162. General Description of Indian Alluvial Rivers.

(*a*) *General Remarks.*—It is probable that all rivers of the first magnitude as they approach their outfall, the sea, pass through the alluvium they have brought down, and, finally, terminate under deltaic conditions. In these lower parts they should therefore have much in common in regard to their characteristics, but their behaviour may be differentiated by the geological and meteorological variations of their catchments. This chapter is therefore limited to the discussion of the physics of only one class of alluvial rivers, namely, those of Upper India. These rivers take their rise in the vast Himalayan range, where they have a torrential nature; thereafter they descend through large plains with a greatly reduced and generally decreasing gradient, where their course is distinguished by the existence of many roughly parallel side channels; lower down the rivers have more defined main channels, and, eventually, near the sea, they form deltas through which they discharge themselves in numerous divergent channels. At their source they are fed by the melting of the snow on the mountains and lower down by local rainfall. The Indus is peculiar in that it flows for the last 550 miles of its course through a nearly rainless area—the Province of Sind.

(*b*) *Characteristic Vegetation.*—Mr. G. M. Ryan [1] states that there are the following five stages in which land is formed by an alluvial river, and that each of these on the lower Indus in Sind is characterised by different kinds of plants or their absence:

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[1] "The River Indus and the Best Method of Embanking It," by G. M. Ryan, F.L.S., Indian Forest Service; "The Indian Forester," Vol. XXII, No. 4, April, 1896.

1st Stage.—Muddy swamps — mangrove (*Avicennia officinalis*).

2nd Stage.—Sand and clay deposits, frequent overflows —tamarisk (*Tamarix Gallica*).

3rd Stage.—More sand, rare overflows—babhul (*Acacia Arabica*).

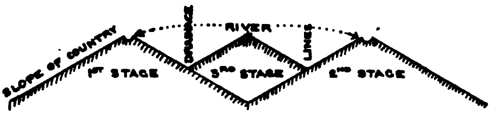
4th Stage.—Above the reach of floods, river channel deepening itself and becoming less tortuous—khandi (*Prosopis spicigera*), with roots 60 or 70 feet deep, which draw water from subsoil percolation.

5th and Final Stage.—River bed scoured deeper and khandi dies down, thus the land becomes high, dry, and treeless.

(*c*) *Formation of Country by the River.*—The leading features of an Indian alluvial river are the large amount of silt it brings down and the insufficiency of its channel to contain its flood water. In consequence of these during floods there are large spills over the natural unbanked banks, which overflows as the velocity of the water is reduced, at once commence to drop their silt, and, as they become thus clarified, continue to deposit it in gradually decreasing quantity the further they proceed from the river. Thus a cross-section of the country would show the river running at the highest point and the land falling on each side of it at a very gentle slope (Fig. 80). In course of time the river would break through one of its banks and assume a new course, when the same raising of its banks would take place. A valley would thus be formed between the two courses, and this itself would eventually be obliterated by the river breaking into it and similarly silting up the area. This action of gradually raising the country to a large plain by successive deposits of silt along different courses of the river occurs chiefly in its deltaic portions, but may also continue higher up after that upper part has emerged from the deltaic stage, when the river

FIG. 80

DELTAIC FORMATION



breaks through one of its banks and takes an entirely new course.

The silt is of a very fine, unstable character, and thus the river flows in a channel the bed and sides of which are quite unable to resist any violent attack on them by the water. Were the river's discharge to be fairly constant, a more or less permanent regime might eventually be established; but this is far from being the case, for during the flood season it may be fifty to one hundred times the minimum low-water flow. In a maximum flood the width may be ten to twenty times, and the velocity and silt in suspension several times, what they are during minimum low water. Not only are the floods excessive, but they vary in amount and duration; the great fluctuations in discharge are thus continually changing the conditions, and it is the floods which principally affect the regime of the river. As will be explained later on, the bed and banks, the gradient, depth, velocity, and course of the river are thus perpetually altering, as there is nothing which can resist its attack. These different characteristics are to a great extent interdependent, so that in describing them some repetition is unavoidable.

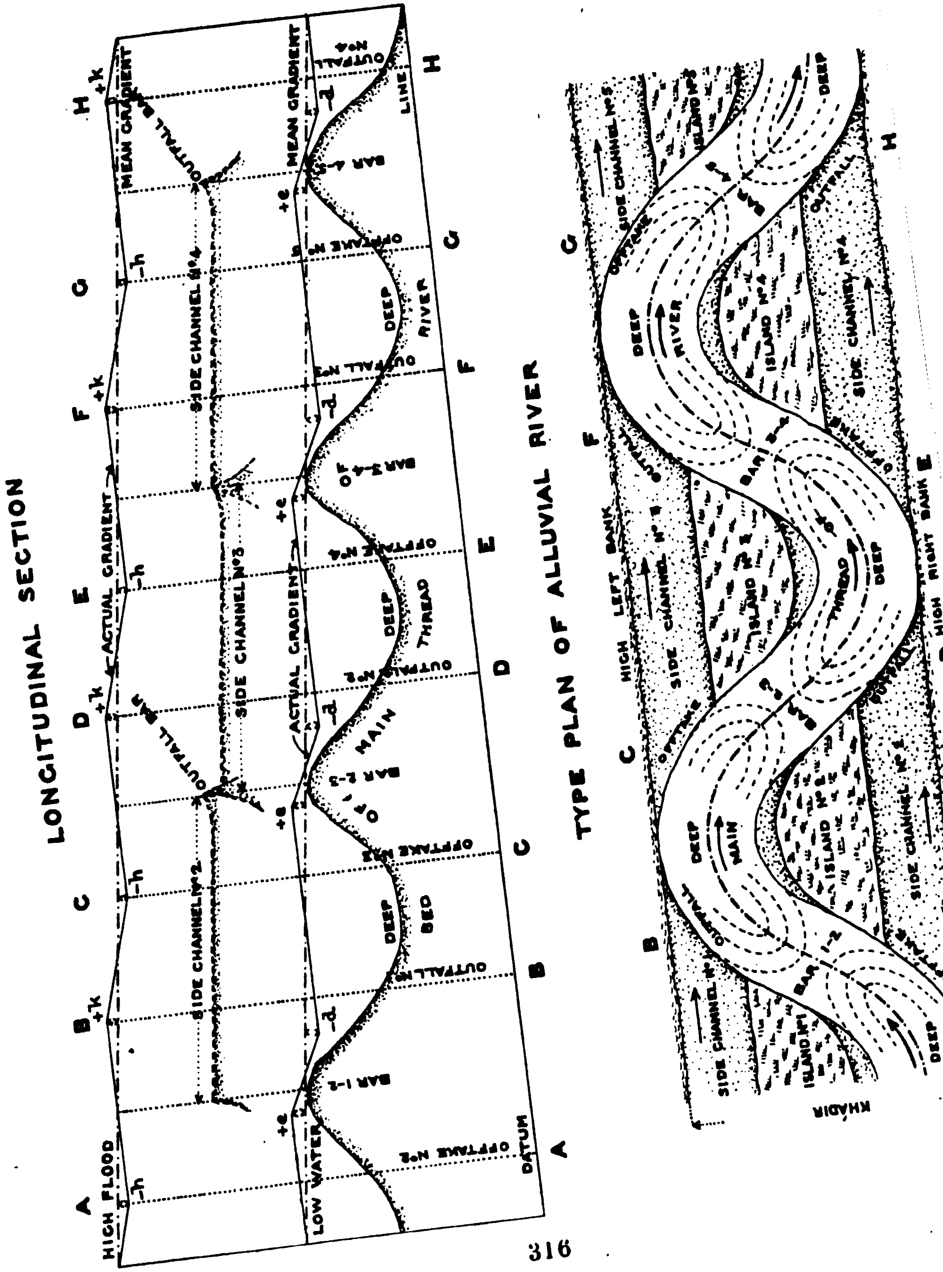
(*d*) *Slowness of Formation of Country.*—While there are constant local changes, so far as observation has gone it has been stated there is not in the upper parts of the river any noticeable change in its length nor elevation of its bed when a considerable part of its course is taken into account. This may be likened to a long steel tape fixed at its ends and lying sinuously between them; any alteration of one of its curves will affect the others without its general length being increased. However, it may be doubted if observations have anywhere been conducted long enough to establish the truth of the dictum, and the evidence of the way the country has been formed is against the alleged non-raising of bed level. In the deltaic portion there is considerable increase in length and elevation, and it is believed the Indus in the last 150 years has lengthened its course by some 80 miles, leaving the old sea port of Tatta some 60 miles inland, and with the river flood surface opposite to it some 38 feet above sea level. Generally, the meanderings of the river increase in total length the nearer the sea is approached; that is due to the increasing fineness of the silt, but the effect of this in causing sinuosity is partially neutralised by the decreasing gradient.

(*e*) *Changes of River's Course.*—Even when the river has attained on the whole a permanent course, it still continues to form the country by pouring silt on to it during the flood season. Were that course permanent in detail, the raising of the land by the deposition on it of silt would be confined to a comparatively narrow strip bordering the river ; this restricted action is probably effected by a system of flood embankments close to the river, as long as these are not eroded. The limited amount of raising is, however, prevented by the constant changes in detail of the unembanked course of the river whereby old land is cut away, first on one bank and then on the other, and new land is thrown up on the opposite bank by the sinuous wanderings of the river, which thereby is enabled to raise by silting a much broader area of country. There are wide limits to these wanderings, which are the result of the varying factors influencing the river's course, in the same way (Art. 52, end of (*e*)) that the high-flood discharge of a river takes into account and is due to all the factors producing it. The river is not likely ever to exceed those limits, but within them it is fairly certain to invade again at some time the areas it has previously occupied. This is a most important fact to be borne in mind when constructing flood embankments (Art. 193, end of (*a*)). Occasionally the limits are defined by bluffs of high land, but those in India being generally formed of erodible soil are but limits of, and are not barriers to, erosion. There this high land is known as the "bár," in contradistinction to the "khádir," or riverain low land.

(*f*) *Hydrographic Observations Necessary.*—In order properly to deal with a great alluvial river subject to violent fluctuations of its course, which may damage or even render useless costly works, such as railway bridges and irrigation weirs, it is essential that it should be carefully surveyed annually, and that all hydrographic observations connected with its discharge, velocity, gradient, scour, erosion, silting, and curvature, etc., should be made for a considerable series of years, until the facts influencing its regime are established. The greater the length of the river which can be kept under survey and observation the better, so that the effect of variations in one part of its course on other parts may be studied properly. To omit certain parts because they do not immediately affect irrigation interests may prevent a correct appreciation of the causes at work which have eventually an influence on them. On the Mississippi

FIG. 81

MOLLOY'S RIVER REGIME THEORY



the American engineer is concerned with the protection of long lengths of the river; in India, where the land is not valuable enough to justify the cost of such protection, the Indian engineer retires his embankments when the river threatens them, and holds only definite points such as bridges and weirs. A hydrographic survey will be as useful for determining the amount of retirement and the proper alignment of embankments as it will be for locating the best sites for bridges and weirs; the cost of research will be many times repaid by the security of the works and of their dependent interests which it will ensure. Comparatively little scientific investigation has, however, been carried out in India, and much loss has thus resulted. Certain theories of river regime which have been evolved are described below.

163. Molloy's River Regime Theory.[1]

(*a*) *The Course of the River.*—Figure 81 in plan and longitudinal section illustrates this theory. Taking the plan first, it will be seen that the typical river bends alternately from one bank to the other. At the crest of each bend is deep water, and in the lengths where the river changes over from one side to the other shallow "crossings" or "bars" are formed by the deposition of silt in the bed. These bars are produced by the action of the side channels, as explained below. From above a bar to below the one downstream of it is a "side channel," the upstream end of which is called its "off-take," and the downstream end its "outfall"; such a type channel may actually consist of several minor and shallow meandering ones. Between the side channels and the main river are "islands." During the low-water season the side channels may be dry, or have only a small flow; as the river rises in the flood season, their flow increases, and, if the flood discharge in them is sufficiently prolonged, they may deepen during the subsequent fall of the river, by cutting back from the outfall, and enlarge by side erosion until they may pass a considerable portion of the whole discharge. If this action is continued long enough, the side channel may become the main channel, in which case the original tortuous course will be abandoned by the river in the succeeding low-water season and may be silted up. During the low-water period the surface falls follow the bed falls; in the flood season the bed irregularities lose much of their influence, and the surface takes a more regular slope.

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[1] Technical Paper No. 118. by the late R. A. Molloy, Executive Engineer, Punjab Irrigation Department. Govt. of India, Central Printing Office, Simla.

(*b*) *The Levels of the River.*—Then, considering the longitudinal section, it will be noticed that the mean gradients of the high-flood and low-water are represented by chain-dotted lines, and that the actual gradients of the different portions of the river are shown by firm lines that alternately rise above and fall below the mean gradients to a certain extent, which, for the sake of clearness, is much exaggerated in the diagram. Further, that the rises above and falls below the mean gradients take place in opposite directions in regard to the high-flood and low-water mean lines respectively. This variation is thus explained.

Taking the low-water gradients first into account, it will be seen that, owing to the obstructions to flow offered by the bars, compared with the mean gradient, the actual gradient is raised above the bars by an amount indicated by $+ e$, and is depressed below the bars by an amount denoted by $- d$, in order that the water may gain sufficient velocity to pass down the bars. In other words, compared with the mean gradient, the actual gradient is flattened above each bar and steepened over the bar.

Next, to understand the reason for the variations from the mean gradient of the actual high-flood gradient, let a be the low-river discharge, x the flood discharge of the side channel, and b the balance flood discharge carried by the main channel. Thus the total flood discharge being $a + b + x$, the main channel carries $a + b$, and the side one x; this last named leaves the main channel at the off-take above the bar upstream, and rejoins it at the outfall below the bar downstream. Where x is abstracted from the main channel, the actual gradient of the latter is lowered below the mean gradient to an extent denoted by $-h$, and where x is returned to that channel the actual gradient of the latter is increased above the mean gradient by an amount marked $+ k$. Thus the tendency in the flood season is for the whole flood discharge, $a + b + x$, to pass down the bends of the main channel with an increased velocity, which will deepen those portions, while over the crossings the flood discharge will be reduced to $a + b$, which will flow with a lessened velocity that will cause silt to be deposited in those lengths.

While the flood is rising and the bars are silting, the discharge x down the side channels will tend to increase, which tendency will be partly checked by the rise $+ k$ of the main channel at the outfalls, and the fall $- h$ at the off-takes, which together flatten the gradient of the side channel; but this will be counterbalanced by the effect of the shortness of the direct side channels compared with the length of the tortuous main one. Further, during the rise of the flood, the tendency of x to increase will be reduced by the backflow of the main channel towards the outfalls of the side channels, causing silt to be deposited there so as to form " outfall bars." As soon, however, as the flood begins to fall, $- h$ tends to become $+ e$, and $+ k$ to $- d$ thereby increasing the gradient down the side channel, and, by the greater velocity thus induced, removing the silt deposited near the outfall ; moreover, the water ponded up by the outfall bars will thus be set free, and if its amount is considerable, it will aid substantially in deepening the side channel by scour. Thus, while b, the flood increment down the main channel, decreases after the termination of the flood season (which tends to cause that channel to silt), x, the flood flow down the side channel, diminishes in very much less proportion, and if this flow is maintained for a sufficient time will scour out and enlarge that channel. In the final stage the discharge of the main channel is drawn into the side channel, and a " cut-off " takes place, whereby the entire course of the river is changed. After such a cut-off has occurred, the whole gradient of the river near and above it is lowered by the decrease in its tortuosity, which lowering may be denoted by the expression $- l$. Conversely, anything causing an increase of the tortuosity of the river will raise that gradient by an amount which may be called $+ l$. The intermediate stage, when the velocity of the river has adjusted itself to the physical conditions, and there is neither shortening nor lengthening of the course, is termed *zero*.

(*c*) *Definitions.*—Mr. Molloy thus (with a few petty verbal modifications) defines the terms he employs for variations in river gradients :

$-h$ = the lowering of surface of the main streams due to discharge having been drawn off by a side channel.

$+k$ = the corresponding rise in surface level at the outfall of a side channel where its discharge rejoins that of the main stream.

$+e$ = the heading up above the off-take (and the adjoining bar below it) of a side channel the discharge of which is reduced or stopped altogether.

$-d$ = the lowering of water surface at the outfall of a side channel which becomes dry or is closed.

$-l$ = the general lowering in levels of the surface and bed caused by a cut-off.

zero = the condition between a general lowering and a general raising.

$+l$ = the general raising of level of the surface and the bed due to an increase of the tortuosity of the river.

(*d*) *Variations of Discharge the Cause of River Changes.*—Mr. Molloy's theory is naturally one based on general ideas, but it is the result of careful observation continued for many years, and explains much which occurs; it is thus very useful. Naturally, the illustration and description of it are, for easy comprehension, reduced to the simplest conditions. In an actual river there may be numerous variations in curvature, gradient, etc., and many side channels; these natural conditions complicate matters, but do not vitiate the theory. It indicates very clearly how unstable is the regime of an alluvial river, and how greatly that instability depends upon the great variation of the discharge during the high-flood and low-water seasons. He states in his seventh paragraph: "Such inequalities in the range of rise and fall are only to be accounted for by great variation and disturbance of momentum. Usually, the implied postulate of all river formulæ is absolute uniformity of condition, section, gradient, and velocity. But the actual characteristic of such a reach of such a river" (an alluvial one) "is irregular alternations of all the conditions and consequent changes of momentum. The term channel does not apply to such a river; it is rather a series of pools, or compartments, of which the sides are the high-level islands, and the bar crossings are movable, transverse panels—panels very difficult to move." The incessant and often considerable alterations in surface slope, frequently producing violent changes in the course of the river, are principally due to these bar crossings, and spills down the side channels leading to cuts-off are the great disturbers of the general regime of the river and the great undoers of the work of the low water-stream. Although the "compartment theory" of an alluvial river holds good for much of its length, there are reaches to which it does not apply—in them the width is too small to allow a middle bar to be formed, and the whole flood flows in a concentrated mass parallel with the banks. At such places the course is a stable one, there are very little erosion and change of course, while scouring has merely a temporary effect in removing silt which was deposited before the flood season, and will again be deposited after it during the low-water period.

164. Oldham's River Regime Theory.[1]

(*a*) *The Four Principles.*—Mr. Oldham states that his theory, which he independently puts forward, enunciates principles that had previously been established by M. Dausse,[2] a French engineer. The following are the four principles which he considers apply to alluvial rivers:

1*st Principle.*—Every stream tends to a condition of equilibrium in which the velocity developed is just sufficient to enable the stream to transport its solid burden. If the velocity is initially in excess, the stream will cut down its bed, thus reducing the gradient, the velocity, and the silt transporting power; if the velocity is in deficit, part of the silt will be deposited, thus raising the bed until the gradient is increased enough to produce the velocity required to transport the silt.

2*nd Principle.*—Every stream is alternately collected into a single deep and well-defined channel, or " reach," or spread out into a shallow sheet, or split up into several channels (*vide* Fig. 82) forming a " fan." Where the suspended silt is coarse grained, as in the upper quicker-flowing parts of an alluvial river, the alternate reach and fan are easily seen; where the silt consists of fine sand and clay, as in the lower, meandering parts of such a river, the reach and fan formation, although it exists, is less distinct, and the consequent effects are less pronounced.

3*rd Principle.*—The gradient of the stream is not a uniform one. The bed will be flatter in the reaches (which have a good cross-section and are deep, thus developing velocity), and will be steeper than the mean gradient in the fans (which have a bad cross-section and are shallow, thus reducing velocity).

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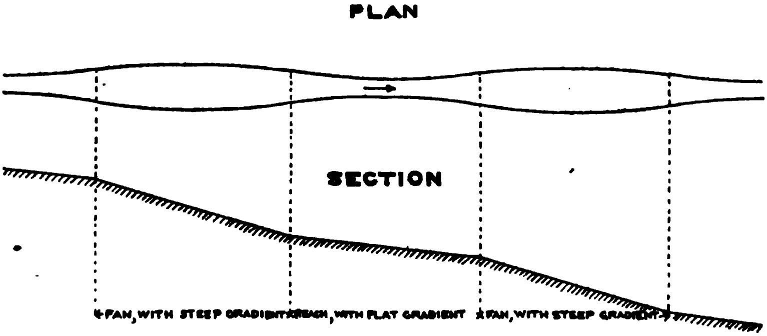
[1] Memorandum on the Indus and the Dera Ghazi Khan district, dated March 27, 1902, by R. D. Oldham, Geological Survey of India, Government of India Central Press, Simla. Also see *Journal of the Geological Society*, Vol. XLIV.

[2] " Études relatives aux Inondations et l'Endiguement des Rivières," published in 1872 in Vol. XX of the " Mémoires présentés par divers Savants à l'Institut de France."

FIG. 82

OLDHAM'S RIVER REGIME THEORY



4th Principle.—Both reach and fan work gradually upstream; the reach encroaches on the upper fan by erosion, and is encroached on by the lower one by silting.

(*b*) *River Action at Protective Works.*—Mr. Oldham states that the above apply to a river in its natural state. If, however, there is on one bank in a fan a stone-faced protective work, as soon as a minor current impinges on it, scour will take place along its face, and a deep channel with flatter gradient than that of the general fan will be formed alongside it. Owing to the difference of level thus brought about, water from the side of the fan will be drawn into the deep channel, and with its discharge thus increased, that will scour and extend its head more rapidly upstream, thus forming a reach of its own. While this deepening is taking place upstream, there will be a check of velocity in the scour channel downstream, where it meets the natural downstream reach of the river, which will cause silt to be deposited at its own tail. Thus the tendency will be for both the silting up of the tail of the scour channel and the scour of its head to progress upstream until the deep channel of the upper natural reach of the river above its fan is met by the latter, and the velocity of that is thereby checked. The whole of the scour channel will thus be silted up and the fan of the river will be re-established as formerly until a minor current again impinges on the protective work and the action described recommences. During the life of the scour channel the current of the main river will be drawn towards it, and, when the scour has travelled beyond the upstream end of the protective work, will tend to produce an embayment of the river above it, which may outflank it if the action is sufficiently prolonged. Also, if the protective work does not extend below the bed of the scour channel, it will be undermined thereby. (These observations have general reference to what may occur at a guide bank (Art. 182), although they were originally made in regard to the destruction of the protective works and the erosion of the right bank of the Indus, which eventually destroyed the town of Dera Ghazi Khan in the Punjab.) Mr. Oldham concludes his remarks by saying that protective works should be continued well upstream of the area to be saved, as it is the head, and not the tail, of the scour channel which requires attention to be paid to it.

(*c*) *Mr. Molloy's Criticism.*—Mr. Molloy, in reviewing Mr. Oldham's note, agrees with his first three principles, which he says are generally held by hydrographic observers. He does not agree with the fourth principle and the application of it to protective works, which account exaggerates the phenomenon of the " attraction of banks." This is the name given to what occurs when a channel is contracted and confined by longitudinal embankments, whereby currents are attracted to them, and cause a deepening of bed along their toe (see Art. 179 (*b*)). He considers scour generally takes place downstream, and is primarily caused by cuts-off producing a draught, $-h$ (Art. 163, middle of (*b*) and (*c*)), and that to stop scour spills should be closed and the water surface, $+e$, thus raised. In other words, the high-flood and low-water courses of the river should be made to coincide so that the high flood may scour out the bars which impede the low-water flow. (Mr. Oldham has not noticed the caving action of the river and the formation of cuts-off, which are leading features of Mr. Molloy's theory.) Mr. Molloy would accept the fourth principle if it were stated to be that " retrogression of levels " works upstream ; this occurs when a side channel (Art. 163 (*a*)) commences to erode at its outfall and that channel cuts itself back, i.e. upstream. After the cut-off has been established, erosion is usually more violent above it, while below it a foreshore with flatter gradients is likely to form. A " fan " or " bar " in the bed at the crossing between two reaches differs essentially from a foreshore on the bank and in the way the river flows over them. The travel upstream of the scour of a fan may take place to a small extent during the low-water period, but in the flood season the conditions are reversed.

165. Other Theories.

(*a*) *The Tributary Theory.*[1]—Mr. Ellis says that a river bends to the infalls of its tributaries owing to its bank being there blank, and thus weak, and the tributary forming a channel on that side. (Presumably he considers the off-take of a canal has a similar effect. In alluvial rivers, however, the bends at canals are occasionally reversed by changes in the course of the river, with disastrous results to the working of the canals. Moreover, there the sectional area of even a large canal bears a very small proportion to that of the river in flood. The inflowing action of a large tributary at its confluence may well produce some effect on the course of the river, but that would tend to deflect its current to the opposite bank.)

To bring the river under control, he says some points should be firmly fixed, and no tributary streams should be allowed to enter nor irrigation canals to take off from the river except at fixed points. He observes that the conditions which usually obtain are:

(i) No stream coming in on either side—a straight, well-defined channel.
(ii) Streams coming in on one side—a well-defined channel on that side only.
(iii) Streams coming in on both sides—an ill-defined channel and a disposition to form a shoal in midstream.

(In Indian alluvial rivers the predominant causes of change of course are the great fluctuation in their discharge between high flood and low water and the large amount of silt carried; these create changes of gradient, velocity, cross-sectional area, and curvature. There is no stability of regime in the natural course, and the bends thus vary in position and direction in different years, as the conditions of flow alter and are influenced by the changes of alignment of the river in the neighbourhood.)

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[1] "The Causes of River Deviation," by T. S. Ellis, *The Engineer*, Vol. CXII, No. 2920, p. 206, dated December 15, 1911.

(*b*) *Direction Theories.*—Mr. Parker[1] states that in the Northern Hemisphere rivers flowing to the north attack the east bank, and those running to the south the west bank, i.e. in both cases the right bank. He has not noticed what is the effect on rivers flowing either west or east. As examples bearing out what he has said he instances the Nile, flowing north, where the west bank was first reclaimed, and Punjab rivers, flowing south, on which, with the exception of the Western Jumna, all canal heads are situated on the east bank.

Another theory is that rivers running north or south attack their west banks owing to the rotation of the earth bringing those banks against the current. This assumes that the water of the rivers does not acquire the same rotatory motion as does the land, which assumption does not appear tenable. The destruction of Dera Ghazi Khan on the west bank of the Indus was said by some to be due to this cause; Mr. Molloy held with much greater reason that the westerly trend of that river there was owing to its deflection by small reclamation banks on the eastern side, which were maintained year after year in the interest of cultivation.

166. Erosion.[2]

(*a*) *Definitions and Classification.*—The terms "erosion" and "scour" are generally used interchangeably; it will, however, be clearer to give each a separate and distinct meaning. Thus erosion may be defined to be the destructive effect caused by the river's lateral action on riparian land and works, and scour, that due to the river's vertical action on its bed. Although the two forms of destruction can be dealt with separately, they have a mutual influence on each other; thus an excessive amount of embayment in the river bank by erosion may lead to a cut-off and scour in the river bed, while a great deepening by scour may cause a straightening of the river's course. Thus defined erosion and scour may be said to be of three kinds:

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[1] "The Control of Water," by Philip A. Morley Parker, 1913, p. 666.

[2] For much of what is stated in paragraphs 166 and 168–175, and the illustrative figures, the author is indebted to "River Training and Control," by Mr. (now Sir) Francis J. E. Spring, Technical Paper No. 118, Government of India Central Printing Office, Simla, 1903.

(i) Normal, caused by straight, unobstructed currents parallel to the river's bank. Such erosion proceeds gently and regularly, and may deepen the river channel next the bank from 30 to 40 feet below low-water level.

(ii) Abnormal, caused by straight-flowing currents impinging at an angle against the river bank. Such erosion produces caving, or embayment, of the bank, and may be rapid; it may deepen the river channel next the bank from 60 to 100 feet below low-water level.

(iii) Extraordinary, caused by rotatory swirls set up where the onflowing currents are bounded by dead or non-flowing water. Such erosion is extremely destructive locally, and may deepen the river channel where it occurs from 80 to 120 feet below low water.

(*b*) *Works to resist Maximum River Action.*—This classification is important, as works to withstand the action of the river must be designed to meet the conditions which may occur. They will be destroyed if they are undermined, and therefore must extend well below the probably greatest depth which may take place. The limits of depth given above are due to variations in the character of the sand forming the bed—the larger, heavier, and more angular the sand, the less will be the erosion. The maximum normal erosion must be provided against at all points of a protective work; the maximum abnormal erosion must similarly be met at the special points where the river will attack; extraordinary erosion is not only very destructive, but involves works of great cost and the danger of their failure; care should therefore be taken to design protective works so that they are never exposed to this kind of erosion.

(*c*) *Causes of Erosion.*—When the bank and the river are straight, even normal erosion will not usually take place unless there is an underlying sandy layer which may be lapped away. Unfortunately, such layers generally underlie most banks and form a great element of weakness, as they do not offer any resistance to erosion.

Abnormal erosion is caused by anything which may deflect the current on to the bank, e.g. a cut-off causing a rapid stream to impinge at an angle on the bank, or a shoal on the other bank, diverting the course of the river away from that bank. Where a crossing exists oblique to the general axis of the river channel, it will deflect the current on to a bank and cause caving, which will progress downstream until the point of reversion is reached (which may be due to the next lower crossing). The crossings or bars have themselves a tendency to travel downstream. The smaller the angle of attack, the less will be the erosion, other things being the same. This form of erosion proceeds by " caving " or " embayment," the river bank being scooped out in large curves, and generally progresses downstream, but may go upstream.

Extraordinary scour producing violent erosion is dealt with in Article 169.

The principal factors on which erosion depends are: the velocity of the river, the duration of its flow, the nature of the material of the bed and banks, the angle which the current makes with the bank, and the curvature and general alignment of the bank.

Erosion is due to the local lowering of the surface and the bed. A rise of surface level often reduces erosion, and, when this is combined with reduction of velocity, erosion must stop.

(*d*) *Damage caused to Cultivation.*—Erosion is a great source of loss to cultivation, as a large extent of agricultural lands and the villages themselves may be swept away in a single season. The value of the area in India is, however, not great enough to justify large expenditure on protection, even if that were feasible. Moreover, the inhabitants are accustomed to the constantly changing conditions under which they live, and recognise that an alluvial river, despite its vagaries, is a blessing rather than a curse. What it removes at one place by erosion it restores at another by accretion ; it fertilises the land by the silt it pours over it, and alone renders cultivation possible in rainless areas by the water it supplies in the most convenient manner for irrigation.

167. Observations of Erosion.

The following notes on erosion were made from recent observations and surveys of the lower Indus in Sind :

(i) The progress of erosion at any point is usually determined by the conditions of the river upstream.

(ii) Erosion generally proceeds downstream, but may travel upstream if the configuration of the opposite bank thus deflects the attack of the river on to the caving bank.

(iii) Erosion follows the direction of the main current of the river when that impinges on one of its banks.

(iv) Where the river is confined to one channel, erosion does not take place on both banks in the same locality at the same time.

(v) Erosion on one bank is generally accompanied by accretion of equal extent on the other bank.

(vi) Erosion is most severe when a bank which consists of clay or heavy soil at the top is underlain by sandy strata which can readily be undermined.

(vii) The roots of vegetation by binding the soil together exercise some protective effect against erosion so far as they extend, but none below this. Unfortunately, on riverain areas undergrowth and trees are generally shallow-rooted.

(viii) When the river undermines deeply a tree-clad area, erosion is not likely to be retarded, except temporarily, if the fallen trees act as groynes and the water subsequently falls rapidly, but will probably be accelerated by the presence of the trees, which will act as a surcharge on the caving bank.

(ix) Erosion is most active during the flood season, and is sometimes violent during a sudden rise of the river.

(x) Erosion is generally more active during a falling than during a rising stage of the river, as in the former case the unsubmerged and overhanging bank is charged with moisture, which weights it and diminishes its cohesion.

(xi) As a rule, after the river tops a bank, erosion greatly diminishes and often ceases, as then the whole of the earth is supported by the water.

(xii) Erosion is less rapid below than above Kotri (150 miles from the sea), and thus varies in extent directly with the gradient of the river.

(xiii) Erosion is most pronounced on the concave side of a curve, as that is exposed to the action of a concentrated current.

(xiv) Erosion is, however, rarely very active on river bends where the curvature is very sharp, as the main current does not there hug the bank.

(xv) The general tendency is for the curvature of erosion to become easier, but when that is very sharp, a " cut-off " may occur across the bend. This, by shortening the course of the river and thus increasing its gradient, will lead to the formation of new curves, which will usually be produced downstream.

(xvi) The maximum curvature of erosion has a rise equal to about two-thirds of the chord; minor embayments on main curves may also have this proportion of rise to chord.

(xvii) To a considerable extent a projection of stiff clay or firm soil can resist the erosive action of the river.

(xviii) An embayment is, almost invariably, formed just below this point, owing to the swirl of the water produced by the obstruction.

(xix) If this embayment becomes sufficiently deep, the projecting point will be outflanked and washed away.

(xx) If the erosion continues after the destruction of the hard projection, it will take place upstream thereof and the river will thus form a large curve, including its previous downstream embayment. In this way the main curve is often enlarged by the absorption of small embayments down its course.

168. Scour.

(i) In Article 166 scour was defined to be the destructive effect due to the river's vertical action, i.e. in deepening its bed, while erosion is that which affects its banks by horizontal action. Scour may follow on erosion, as a deep channel will usually be formed at the foot of a caving bank.

(ii) Scour depends chiefly upon velocity (and that upon gradient and cross-section), but also greatly on the amount of silt carried by the river; if that is in excess, there will be silting; if that is in defect there will be scour; and if there is only just the amount of matter suspended in the water which its velocity will enable it to carry, there will be neither raising nor lowering of the bed. Thus scour is worst during a falling river, because the water then contains a small amount of silt; during a rising river the water is charged with silt, and this tends to fill up hollows in the bed.

(iii) Deep channels are likely to become deeper owing to the concentration of flow down them, especially when the water is not fully charged with silt.

(iv) When a flood is at its maximum it has already deposited some of its silt upstream, and will therefore tend to scour; thus a river may be deepened, although both the flood level and the velocity have decreased.

(v) When a hard, unerodible bank is under attack by the river, a deep channel will tend to be formed along its toe, as the velocity may scour away the bed, while the bank will not furnish fresh sand to replace the removed material. If, however, there is a caving bank under erosion, it will supply sand, and the scour channel may thus not deepen.

(vi) An unerodible covering protects the bed from scour; thus a ruined masonry structure, dumped stones and refuse, or matted vegetation, will tend to prevent scour under them.

(vii) The removal of such a covering (such as by clearing off the vegetation and ploughing up the soil) will induce scour, as the scouring effect depends upon the nature of the bed as well as upon the velocity of the water.

(viii) The element of time during which scouring action continues greatly affects its amount; thus deep channels flowing longer will be scoured more than shallow ones, which will earlier cease to flow. A cut-off may be delayed or prevented if the level of the river falls so much as to leave dry the short-cut channel across a horseshoe bend before it can cut its way back.

169. Swirls.

(i) A swirl, or rotatory eddy, is produced by a forward-moving current brushing past still water, which thus gives the flow a circular motion. An obstruction to the flow of the river, such as a natural projection or an artificial spur, first produces still water either upstream, downstream, or on both sides of it, and this in its turn forms a swirl or swirls.

(ii) The reason why swirls cause deep scour is that they throw off to their outer circumference the silt that was suspended in the water or scoured from the bed, and no fresh silt can enter the swirl area from caving banks.

(iii) Swirls have dead water at their centres, which may cause silt to deposit there; when they occur near a caving bank, silt falls in on the land side, thus raising the bed there; the deepest water is always on the outside of a swirl.

(iv) The destructiveness of swirls depends upon the velocity of the current, the area of still water, the size and nature of the sand of the river bed, and the duration of the flow. It is increased by greater velocity, as the outer and quicker moving part of a swirl always moves a little slower than the current which produces it, larger area of still water (produced by a sharp projection and diminished by a gently curved one which the flowing water follows closely), fine sand (offering less resistance to disturbance), and long-continued flow (allowing erosion to progress, thus deepening the bed and thereby accelerating the velocity), and it is diminished in the degree in which these conditions are reversed.

(v) Swirls are the most destructive form of erosion, and protective works should therefore be designed so as to avoid them and certainly not to produce them. A swirl at Rajghát on the Ganges has been observed to be 200 feet in diameter, the circumferential velocity 11 feet per second, the depression of the central vortex 3 feet below the outer level, and the depth 40 feet, about 50 feet from the centre. Swirls were the cause of the destruction of the Denehy groynes at Dera Ghazi Khan (Art. 180 (*c*)).

(vi) For the proper design of protective works the greatest depths of swirl-scour and bend-scour which occur in the river should be known, and should be ascertained as early as possible after the close of the flood season and before silting up takes place.

170. Silting.

(i) The silt (including sand) suspended in a river is due either to detritus from the catchment area or to local erosion of the banks and scour of the bed.

(ii) The largest particles of sand with the greatest specific gravity and most angular in shape are first deposited, and are therefore found along the upper parts of the river's course. The finest, lightest, and most flaky particles are carried furthest forward, and therefore occur along the lower reaches; they are either brought directly into the river by drainage, or are produced from the larger varieties by attrition when passing down the river.

(iii) A rising river which is charged with silt, silts up low places in the bed; a falling river with a deficit of silt will *en route* pick up material from the bed and deepen that.

(iv) The maximum amount of silt is usually carried by a rising river just before the peak of the flood has been reached; when that occurs, some of the silt has already been deposited in the channel higher up, as then the flood was there at its maximum.

(v) Silt is dropped when the velocity of the river is retarded either by its entry into pools, or by lengths of flat gradient, or by the formation of uprising currents.

(vi) The amount of silt in suspension is lessened when the angle of attack of the current on a bank is reduced, and is increased when that becomes greater.

(vii) The river is constantly dropping its burden at shallow places where the velocity is reduced and near and below caving banks, where the water is overcharged with silt from erosion.

(viii) When the velocity is increased silt is picked up and carried forward, e.g. below a cut-off. Thus the bulk of the silt brought down by the river is continually passing downstream, and the soil conditions of the bed and banks are constantly varying.

(ix) The silting of one part of the cross-section by reducing the area increases the velocity in another part, and thus causes that part to scour.

(x) In a backwater, or abandoned course of the river, the silting, owing to the absence of current or diminution of its velocity, may take place slowly, and may consist of the finest mud, which eventually may form a stiff clay spur, which will be all the harder if indurated by carbonate of lime. Such a spur will resist erosion, and when undermined may fall in hard insoluble lumps, which will protect the bed from scour.

(xi) Similarly, the deposit at the downstream parts of the backwater of a weir may be of a hard, unerodible, clayey nature.

(xii) The gradual raising of the country is effected by silty overflows topping the banks of the river. The maximum deposit takes place at the river's edge where the velocity of the water is first reduced, and the rate of silting diminishes gradually therefrom ; thus the river eventually runs on a ridge line, and the country slopes gently down from it on both sides.

(xiii) The silt deposited on the surface of the country being derived from the top water of the river, will usually be of the finest clayey variety ; it will thus form a hard and erosion-resisting coating, and will consist of sweet, fertile soil. Its deposition and the washing of the inundated area by flood water will keep the land free from deleterious salts, and fit it for cultivation or forest plantation.

(xiv) Below caving banks heavy sand may be deposited on the surface ; as a rule it will be laid on the bed to form a sandy layer, which may eventually be covered with fine sweet soil when the river changes its course.

171. Sand.

(i) Sand is the insoluble part of the river's burden; the soluble part is true silt, which forms soil or clay when it is deposited.

(ii) There is a great difference between river sands; the transportability of sand particles depends upon their size, specific gravity, and shape (Art. 170 (ii)).

(iii) The coarser and heavier the sand, the smaller the amount of scour and consequent erosion which is likely to take place.

(iv) The angle of repose of Upper India river sands does not vary much, i.e. from 31° to 37°; there does not appear to be any law connecting the angle of repose with fineness or coarseness.

(v) The specific gravity of these sands also varies but little, i.e. from 2·63 to 2·74, and similarly there does not appear to be any law relating to it which is of use from an engineering point of view.

(vi) Mr. Spring, by passing sands through sieves having 10, 16, 30, 40, 75, and 100 gauze wires to the inch, classifies them thus:

Very coarse—when 25 per cent of the whole is stopped by the 16-wire sieve;
Coarse—when 80 per cent. is stopped by the 40-wire sieve;
Medium—grades between "coarse" and "fine";
Fine—when 80 per cent. passes through the 75-wire sieve;
Very fine—fine sand of which 20 per cent. passes the 100-wire sieve.

(vii) The proper design of river works depends upon the nature of the sand on which they will have to be founded. To gain a knowledge of that sand truly representative samples should be analysed; it should be remembered that, as sand travels downstream, and the bed and banks may thus be altered in the course of time, the most unfavourable sand in the locality, say 5 to 10 miles upstream, should be examined, and the result of the examination carefully recorded on the plans.

172. Gradient of the River.

(i) The gradient of the river is one of the principal factors on which the velocity of the water depends; others are the nature of the cross-sectional area and the character of the bed and banks.

(ii) The fall of the river is not a uniform one, as its course consists of pools with practically level beds alternating with reaches which have comparatively steep gradients (Art. 163 (*d*)).

(iii) As the character of the river bed is continually changing, by local erosion, scour, and silting, a reach becoming a pool, and *vice versâ*, its gradient is not permanent so far as short lengths are concerned; when, however, long lengths are considered, the gradient may be said to be practically permanent.

(iv) The steeper the gradient, the greater the velocity and the tendency of the river to erode, scour, and alter its course; the flatter the gradient, the more likely is the bed to silt and the course to be preserved.

173. Velocity.

(i) The velocity of the river depends upon the gradient, the nature of the cross-sectional area, and the character of the bed and banks.

(ii) The velocity depends greatly upon the depth (*vide* Fig. 83); thus with the same gradient of 3 inches to a mile, where the cross-section is only a foot deep, the velocity will be under a foot per second; whereas where it is 40 feet deep the velocity will be over 5 feet a second. As greater scour follows increased velocity, the tendency is for the deeper parts of the cross-section to become deeper still, and this will still further increase the velocity until, by the consequent flattening of the gradient, a stable regime is reached.

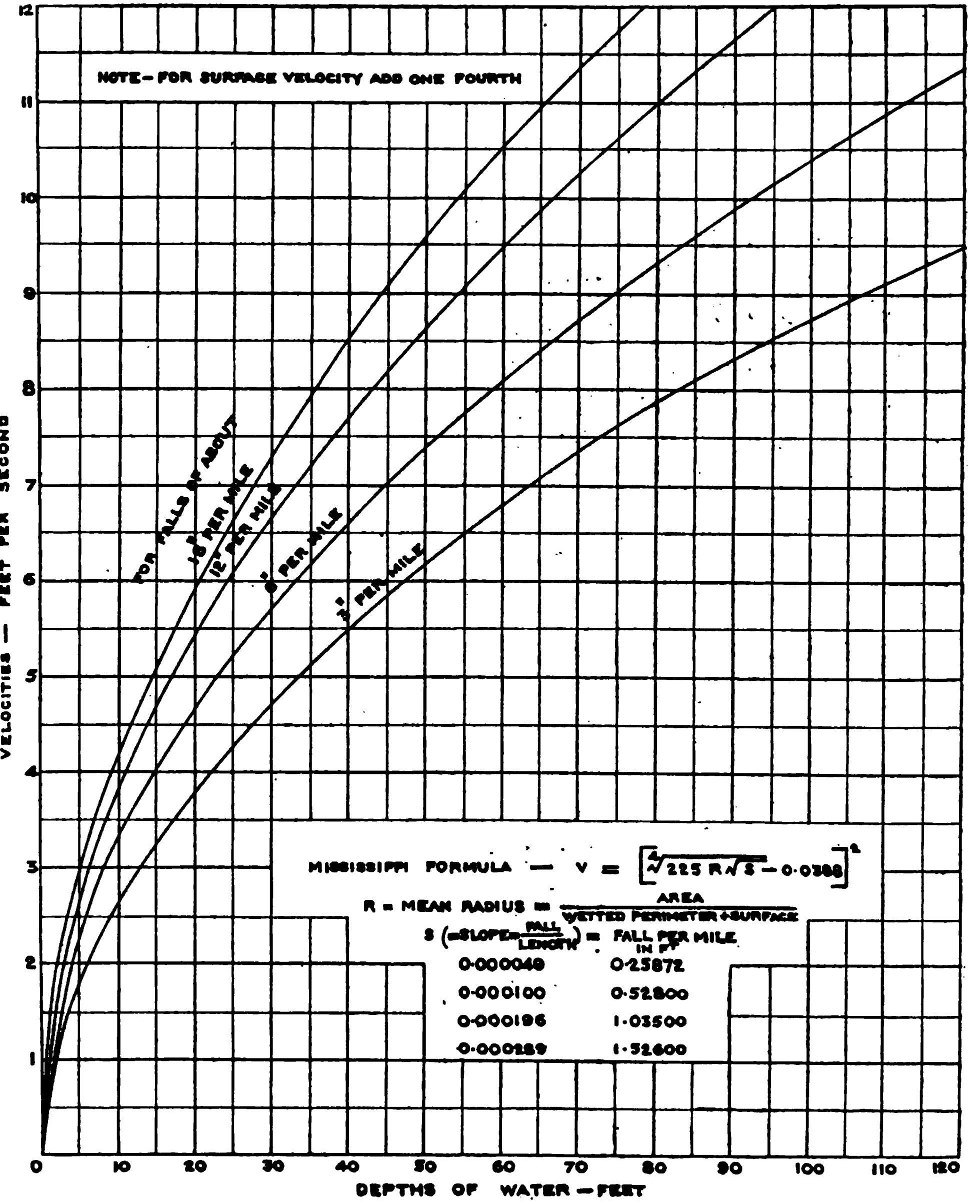
(iii) The velocity of a falling river is greater than that of a rising river. In the former case the channel is draining away without obstruction; in the latter the flood as it rises has to fill the channel, its pools, and finally its reservoir area (Art. 176 (vii)).

(iv) The river has to adjust its velocity to what its bed and banks can stand; as the latter are varied, so also will be the former.

(v) When the velocity is retarded, silt is dropped; when the velocity is increased, silt is picked up.

FIG. 83

CURVES OF MEAN VELOCITIES FOR VARIOUS DEPTHS AND SLOPES



MISSISSIPPI FORMULA — $V = \left[\sqrt[4]{225\,R\sqrt{S}} - 0.0388\right]^2$

$R = \text{MEAN RADIUS} = \dfrac{\text{AREA}}{\text{WETTED PERIMETER + SURFACE}}$

$S\left(=\text{SLOPE} = \dfrac{\text{FALL}}{\text{LENGTH}}\right) =$	FALL PER MILE IN FT
0·000049	0·25872
0·000100	0·52800
0·000196	1·03500
0·000289	1·52600

(vi) The velocity is increased locally by the formation of shoals below pools, which concentrate the gradient there; as the velocity is accelerated, the scouring capacity of the water becomes greater and tends to remove the shoal; then, as the velocity decreases, the shoal is likely to re-form. The formation of the bed thus oscillates until some large change in the river establishes its condition more or less permanently.

(vii) A deep channel scoured out during the flood season may silt up in the succeeding low-water season, as its section will be too great for the reduced velocity then. In the following flood season the silting will at first reduce the velocity below what it was in the previous one; but if the floods continue sufficiently long and are sufficiently intense, they will scour away the deposit and re-establish the former deep channel. If, however, for any reason the floods are decreased and last only for a short time, they may not have sufficient power to scour, and the silting up may remain permanently, and thus affect the flood regime of the river.

(viii) The velocity may be increased below a sudden bend in the river causing the water upstream to head up; as this may alter the regime of the river, such a site is undesirable for the location of a bridge or of a weir.

174. Curvature of the River—Horseshoe Bends—Cuts-off—Avulsions.

(i) The extent of the curvature of a bend of a river depends upon the cohesiveness of the soil of the banks, the fineness of the bed sand, the velocity of the water, and the nature of the cross-sectional area; it is limited when no further tortuosity is required to flatten the gradient, or can take place before a cut-off is established.

(ii) A river consists of a series of curves and straights; at the former it is in a more unstable condition than it is at the latter, and changes are more likely to originate or take place at the curves than at the straights.

(iii) The curves of the upper part of a river, where the gradient is steeper and the sand of the bed large-grained, are sharper than those of the part nearest the sea, where the fall is less, and sand is for the most part replaced by fine clayey silt. The percentage of meandering to direct length of the latter, owing to the largeness of its curves, is somewhat more than that of the former.

(iv) A bend is started by the acceleration of the river over the shoal upstream of it which directs the current against one bank. If the material of the bank were homogeneous and the velocity remained unchanged, the bend would tend to become circular; the material, however, varies, the velocity and the angle of impingement get less, and thus erosive power decreases, while the general downstream fall of the current tends to open out the loop. The main current finally leaves the bank it has previously hugged, and, with the direction given by the last reach, tends to cross over to the other side.

(v) When the curvature of a bend becomes very sharp, the main current does not hug the bank, and tends to find a more direct course.

(vi) The sharpest curve in the locality should be determined by inspection, so that an estimate may be made of the maximum amount of embayment which may take place behind a protective work. The radius of bends on the Mississippi varies from under 1 mile to over 8 miles; those with the smallest radii occur mostly in the lower reaches of the river.

(vii) A very pronounced curve may nearly return on itself, and is then called a "horseshoe bend." The difference of level between the extreme upstream and downstream ends of the neck of such a bend is at a maximum. During floods flood water may pass across this neck and form a side channel, which, if the duration of the flow down it is sufficient, will be widened and deepened by retrogression of levels, or cutting back, so as to become the main channel. Thus there will be a "cut-off" shortening the length of the river, and thereby increasing its velocity; the river will thereafter endeavour to flatten its gradient by forming new curves upstream and downstream (Art. 163, end of (*b*)). Until the gradient is re-established, the river will be in a most unstable condition, and violent action on its banks and bed may take place for several miles.

(viii) A cut-off does not affect the neighbouring cultivators so much as erosion, for it does not cause the destruction of the surface of land previously surrounded by the bend, but merely transfers that land from one bank of the river to the other.

(ix) The local action due to the formation of a cut-off in Northern India is known as an "avulsion," but it would seem more appropriate to reserve that term for one of those rare entire changes of course described in Article 162 (*c*). From its dictionary and legal meaning of "forcible separation" Mr. Molloy would apply the word "avulsion" only to such changes of the river as affect lands occupied by real property, i.e. that alter quasi-permanent conditions which have been in force so long that the inhabitants have raised buildings, formed gardens, etc., on the lands.

175. Afflux.

(i) Afflux may be defined as the difference in level upstream and downstream of a point on a river, which difference is caused by something retarding its flow.

(ii) The artificial narrowing of an alluvial river at a bridge site does not, however, produce an afflux, for as floods in such a river rise slowly, time is given for them to deepen and improve the discharging capacity of the cross-section by scour. The deepening thus effected makes it necessary to increase the width of the apron protection of the guide banks (Art. 185 (*a*)).

(iii) An irrigation weir, extending as it does right across the river as a bar, raises its afflux considerably. The raising may affect riverain lands, and should therefore be reduced as much as possible by giving the weir the maximum length practicable. That length must, however, not be increased so much as to cause islands of silt to be formed upstream of the weir, as these will mask part of its crest, and thus produce increased and irregular flow over the rest.

(iv) The effect of the afflux in the backwater of a weir is to raise and flatten the general gradient of the river, i.e. to produce $+l$ (Art. 163 (*c*)) ; this should lessen in the backwater area the velocity of the flow, and this again the eroding power of the water, the tortuosity of the river and the depth of its embayments. The velocity being checked at the entry into the backwater, heavy sand should be deposited there, and the finer silt be carried lower down. The effect of the current produced by the draw of the weir should be to reduce the silt deposit just upstream of the work.

(v) At a sudden bend an afflux is produced by the river having to acquire increased head to change in direction. This results in increased velocity downstream, and such a bend is therefore unsuitable for the location of a bridge or a weir.

176. High-Flood Level.

(i) The high-flood level under natural conditions of a non-alluvial river, which has fixed bed and banks, depends solely upon its maximum rate of discharge. This rate has a great influence on the high-flood level of an alluvial river, but there are other influences which also affect the level, so much so that it is quite possible in such a river for a flood with a smaller discharge to rise higher than a flood with a larger one.

(ii) A cut-off, as long as it is in operation, by shortening the course of the river, will lower the gradient, and therefore the high-flood level of the length upstream affected by it. The increased velocity down it will further lower that level.

(iii) The more the tortuosity of the river is increased, the flatter will be its gradient, the smaller its velocity, and the higher its flood level in the length affected.

(iv) The curvature of a bend, by attracting the main current to the concave bank, will increase the high-flood level at that bank.

(v) The silting of the bed either in longitudinal or cross-section will tend to raise the high-flood level, partly by contracting the waterway, and partly by reducing the velocity; conversely, erosion and scour will tend to lower the high-flood level.

(vi) A violent wind will heap up the surface of the water against the bank to which it blows.

(vii) As in a high flood the river overflows its banks, part of its then discharge is absorbed in flooding marginal low-lying land. The area thus exposed to submergence gives the river "reservoir capacity"; the more this area is lessened by artificial embankments or increased in height by silting, the less will be the flood restriction of the reservoir capacity and the higher the flood. In the lower parts of rivers, especially when the country is rainless, the natural tendency is for the high-flood discharge to diminish downstream, owing to the side spill which takes place when they are not embanked.

(viii) The high-flood level will be lowered if there are flood escape channels leading away from the river—these, in fact, act as safety valves, and should not be interfered with unless full provision is made for dealing with the increased flood discharge resulting from such interference.

(ix) Anything which affects the high-flood level of a river will react on its flood gradient, velocity, eroding and scouring power, silting capacity and tortuosity.

177. Deltas.

(*a*) *General Description.*—The delta of an alluvial river is the designation given, from its resemblance to the Greek letter of that name, to the portion of its length nearest the sea where the main channel divides into two or more minor channels, diverging from each other in a fan-like manner. Usually, of these minor channels, two are considerably larger than the others, but this is not always the case. These in their turn bifurcate into minor radiating channels, so that at the outfall into the sea there are numerous mouths ; between the channels are drainage lines, more or less defined and continuous, which are due to the silting of the country by flood spills (Art. 162 (*c*) and Fig. 80, p. 313). All these channels have as leading characteristics extremely meandering and varying courses through the fine alluvial sand which they have previously brought down, flood discharges in excess of what they can carry, and ones diminishing rapidly downstream from their heads, owing to spill over their banks, except when one is fed by a cross overflow current from its neighbour. In Article 162 (*c*) it has been explained how silt is deposited by an alluvial river so as to raise the country with flat slopes extending inland downwards from its banks, and that this process takes place most rapidly in the delta. The new land there formed thus consists of a series of ridge lines, along which the channels flow, gently sloping down to intermediate valley-like depressions. Owing to the sea keeping its levels unchanged and the delta continually advancing into it, the gradients of the channels would tend to get flatter and flatter, did not the deposition of silt in their beds higher up practically preserve those gradients unchanged ; similarly, the longitudinal slopes of the land of the delta and of the area upstream of it are maintained by the silt poured on to them during overflows. Another characteristic of the delta is that throughout it the discharge of the channels is affected by the ebb and flow of the tide; the latter, by blocking the outfalls, is probably the cause of the multiplication of the channels. During high tides the water in them overflows its banks and submerges the land ; the natural reservoir thus formed is drained during the succeeding ebb tides, and the impounded water then gives the river greater scouring power to keep its channels clear of silt. Near the sea this frequent submergence renders the land naturally incapable of being cultivated, but further upstream, where the high tides do not cover it, crops can be grown under natural conditions.

(*b*) *Regulation of Channel Discharges.*—The slopes of the upper delta are eminently favourable to irrigation and drainage, while the fertility of the soil is an encouragement to the growth of crops, so that man is tempted to cultivate the area ; but the constant changes of the courses of the channels and the liability to submergence are against him, and he therefore endeavours to alter these adverse conditions. The first improvement is the regulation of the discharges of the channels, so that these may not be increased by scouring and overflows, nor lessened by silting, and may thus preserve their courses unaltered. Attempts to prevent new meanderings by means of spurs have been successfully made in Madras and elsewhere, but are not generally effective, owing to the erodibility of the deltaic mud. The discharges of the different channels can, however, be divided in settled proportion by means of weirs or bars across their heads ; this can be done without great difficulty where the flow is not affected by the construction of flood embankments, which stop the spill that would otherwise occur. Where such embankments exist the discharge is prevented from naturally decreasing downstream, and the flood level of the lower parts of the channels is thus increased. This renders it necessary to calculate the altered flood levels by a system of trial and error, starting with the natural gradients, and revising them after each calculation, which is a laborious but necessary process. Where required, relief from excessive floods can be given by escape channels.

(*c*) *Flood Embankments.*—To avoid submergence of the country, flood embankments are necessary, and, as just explained, those in the downstream parts of the delta may have to be raised to a dangerous height, or to one impracticable from considerations of cost. The embanking of the delta has the disadvantages that it deprives the protected area of much fertile silt ; also, it diminishes the overflow reservoir capacity of the channels, which in its turn lessens the scouring action during ebb tide, and thus causes the beds to be silted up and flood levels to be raised. Successfully to protect a deltaic area from inundation will prevent its being gradually and regularly raised by silt—Nature's method of reclamation—and will thus lead eventually to the formation of a low-lying, insalubrious tract, always liable to submergence by a breach from the raised river channels. Thus to interfere with Nature's operations involves danger, and is out of proportion costly to the benefits temporarily gained. It is therefore advisable not to make the attempt; the inhabitants in a delta, if they are unable to accommodate themselves to the natural conditions in a newly-forming area, should seek more favourable ones elsewhere. This view is now meeting with acceptance,[1] although unfortunately large areas of deltas have been reclaimed artificially. As a concession the cultivators might be allowed to enclose isolated areas with low ring embankments sufficient only to shut out small floods; this, however, involves the risk that these works will probably be raised higher and made continuous with each other unless a careful and constant watch is maintained to prevent such dangerous development.

178. Survey Base Line and Pillars.

In Article 162 (*f*) the desirability of making a careful survey of the course of the river has been pointed out; the value of such a record increases with the number of years during which it is maintained. In an alluvial country, such as Sind, that is traversed by so erratic a river as the Indus, which is continually changing its course, an ordinary riverain survey may not be recognisable years afterwards, as land marks may have been washed away, and comparison with later surveys may thus not be possible. Where such conditions obtain it would seem advisable to establish on each bank a permanent base line, retired beyond all probability of erosion, with which all riverain surveys would be connected. To mark the base lines and obtain fixed observation stations a series of masonry pillars (Fig. 84) of cheap but permanent construction would be erected. Each of these might be, say, 24 feet high, with a theodolite platform at top, and might have a signal standard and ball, say, 12 feet higher still. Access to the platform would be obtained by means of a staircase, which might wind spirally outside the pillar. As each structure will probably be in an out-of-the-way locality, and will seldom be visited, the bottom landing of the staircase is shown raised 6 feet above ground level, and access to it can be had by means of a removable ladder; this arrangement will prevent trespassers from ascending the pillar. At the base inside the pillar might be a benchmark, securely founded, to which a passage way in the masonry would lead. The pillars would be built well

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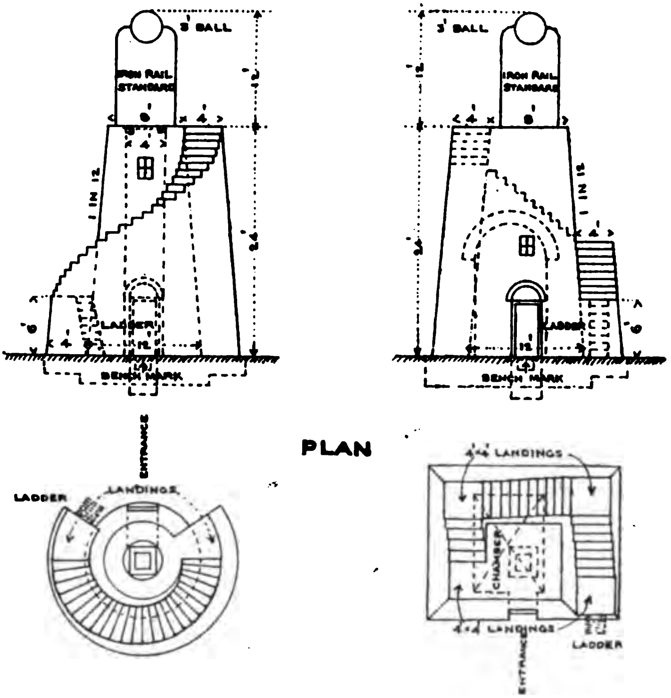
[1] "Drying the huge marshes which lie between the delta of the Tigris and Euphrates on the one side, and the delta of the Karun on the other, could only be compared to getting rid of the safety valve of an engine." Sir William Willcocks on "River Engineering in Mesopotamia." *Morning Post* of 7th November, 1919.

FIG. 84

OBSERVATION PILLARS

ELEVATION



away from all probable erosion at intervals of, say, 10 miles apart, and at prominent places, so that they would not be obscured by trees, etc., and so that each could be viewed from its neighbour on each side, and from one pillar at least on the opposite bank of the river.

CHAPTER XIII.

CONTROL OF LARGE RIVERS IN ALLUVIAL SOIL.

179. Reclamation Bunds.[1]

(*a*) *Principles of Reclamation.*—In the portions of an alluvial river where the bed is very wide and the main channels wander from side to side, the great principles to be followed in reclamation have been expressed thus: "Never throttle, always close and work with a full head." In other words, the river should not have its main channel narrowed; its side channels should be blocked so that they may not develop into cuts-off which destroy the regime of the river; and the full river in the flood season should be induced to pass down the low-water channels so that the low-water conditions may be maintained throughout the year and the floods utilised in scouring out the central sand bars or crossings. The closing of a side channel at once raises $+e$ (Art. 163 (*c*)) of the main channel, and causes that to scour, while at the same time the deepening of the side channel is stopped. If the scour of the main channel continues long enough, a new *thalweg* (or line of deep stream) for the flood discharge will be formed, and then the original raising of $+e$ will automatically disappear.

(*b*) *Effect of Reclamation.*—The closing of scour channels, and, in addition, the prevention of spill over the foreshore, should be effected by what have been called "reclamation bunds," or silting embankments. These depend for their preservation upon the cushions of slack or still water that they produce upstream, which protect them until they are topped or breached, and also cause silt to be deposited over their backwater areas. The bunds, although of a temporary nature, last a long time, and when damaged are easily restored after the river has fallen.. Such repairs should be carried out as soon as possible, so that silting up may continue throughout the succeeding low-water period. Mr. Molloy states that when a stream impinges on another, waves and eddies are produced by the mutual influence of their velocities, which thus destroy each other. This is probably due to the pulsations which always occur in a stream and cause its surface to rise and fall. At the confluence of two streams their pulses do not coincide, and the fluid particles impinge on each other, like bullets fired into a mud wall, without ricochet. When, however, a current strikes a hard bank obliquely, there is afflux, and the fluid particles rebound, as would bullets off a steel target, thus producing helical undercurrents, which scour out a characteristic channel along the toe of a hard bank: that action has been said to be due to "the attraction of banks" (Art. 164 (*c*)). The great danger to be feared in the case of a flood embankment is the general lowering $-l$ of the gradient of the river (Art. 163 (*c*)), which causes scour to take place. This can best be prevented by the formation of a reclamation bund which produces slack water, or a "still-water area," along the flood embankment. The first flooding of a foreshore is by streams at a high level that have low hydraulic mean depth, flat gradient, and consequent small velocity, so that they readily drop the silt with which they are charged and build up the foreshore. This silting up will be accelerated by the formation of reclamation bunds across the foreshore. Even in the scour channels a suddenly augmented flood raises their surface level, decreases their velocity temporarily, and tends to silt them up.

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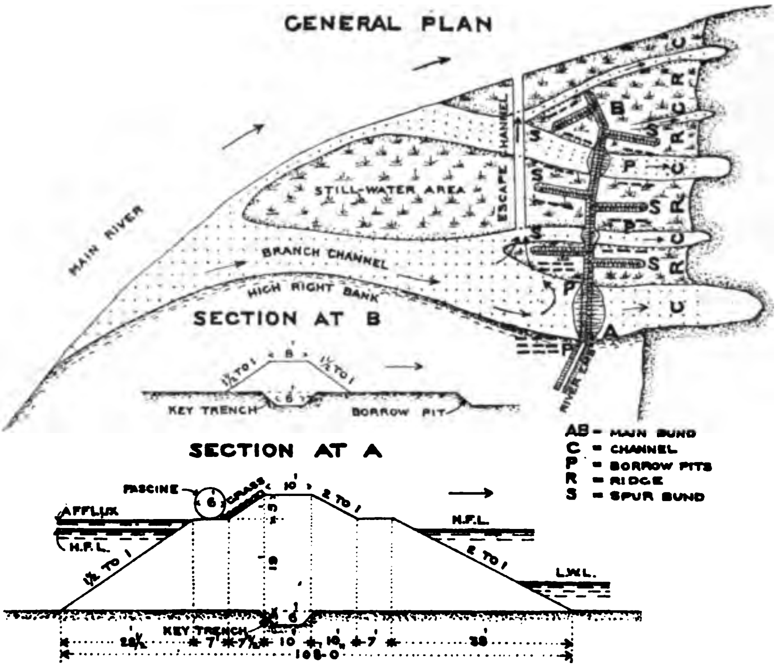
[1] Technical Paper No. 118, by R. A. Molloy, Government of India Central Press, Simla.

(*c*) *Maintenance of Course of River.*—One object of reclamation is to increase artificially the sinuosities of the river, and thus to compel it to preserve its permanence. Reclamation bunds should therefore be formed on both banks, so as to maintain the midstream course of the river, and confine its violent operations to a central zone. The best-known Indian example of the efficiency of such reclamation works is afforded by the small cultivators' banks on the left or east bank of the Indus at Dera Ghazi Khan, which at trivial cost are believed to have deflected the river on to the west bank, thus destroying that town after eroding the works designed to protect it, on which some £150,000 was expended. Reclamation bunds, in contradistinction to guide banks (Art. 182), must be regarded as temporary works, which will require constant attention to maintain them in efficiency.

(*d*) *Design and Construction of Reclamation Bunds.*—Fig. 85 illustrates the plan of a reclamation bund. Mr. Molloy states the highest point of a midstream island (and one best protected (by vegetation)) should be selected for an abutment, into which the bank should be well keyed. The bank should be continued some distance beyond the length to be held,

FIG. 85

RECLAMATION BUND



as some part of its end is likely to be washed away. Where ridges and cross-channels are met, cross-spurs 300 to 500 feet long, should be constructed on the former, both upstream and downstream, so as to produce slack water, especially on the upstream side, in order to induce silting and to protect the main bank. The best material for the construction of the banks is pure sand; failing that, the soil of the locality will have to be used. The material should be obtained from some distance, and preferably on the upstream side, as borrow pits near the bank, and especially downstream of it, greatly endanger its stability; where they exist, screens or hedges should be put up to catch drift sand, in order to fill them up. The axis of the bank should be nearly at right angles to the river, and not less than 60° with it.

A good key trench, 6 to 8 feet wide, should be dug to spring level and carefully filled in. The bank in its highest part should be raised at least 4 feet above flood level, allowing for afflux, with upstream slope of $1\frac{1}{2}$ to 1, downstream one 2 to 1, and top width 10 feet. The less important parts may be of slighter section. To protect the bank from wave-wash, loose fascines of grass and branches of undergrowth, 6 feet in diameter, and bound with wire or string, should be placed on the water face and packed behind with similar loose material.

The surface flood gradient back to the river should be about $\frac{1}{10000}$, and, if necessary, an escape channel with a low-water gradient of from $\frac{1}{2000}$ to $\frac{1}{3000}$ should be dug well away from the bank to ensure this, and to direct all currents from the reclamation bund. This channel should be opened early, so that it may be scoured out during low water, when there will be the maximum head available, for during high flood there will practically not be any cross fall over the area to be reclaimed.

(*e*) *Record of Reclamation.*—In all reclamation work it is of the utmost importance to preserve a careful and complete record of the operations undertaken and observations made. Gauges should be established for determining the surface gradient, and surveys of the river's course and contoured plans of the foreshore should be made (compare Art. 112). This will give a history of the reclamation and show what parts are successful and what fail in their object, and the probable causes of this.

180. Spurs.

(*a*) *General Remarks.*—The earliest form of river control was by the construction of spurs projecting into the current so as to deflect it from places threatened by its attack. Where the banks and bed are fairly hard, this form of protection answers, but where they are not, and consists only of alluvial silt and sand, a spur is of merely temporary utility. It acts in the same way as does a natural hard point (Art. 167 (xvii)), and causes embayment, which tends to cut back and outflank the spur. The first effect of a hard projection producing still water is to cause swirls (Art. 169 (i)) upstream or downstream or in both directions, and these are most destructive, owing to the deep scour which they cause. Backwater swirls behind spurs are more destructive than the direct attack of the river. Advantage of this action has been taken by constructing several spurs about half a mile apart, so as to induce the formation of a continuous deep channel parallel to their ends on their river side. Unless, however, the river ends of the spurs extend below the limit of scour, which there attains the maximum depth, and the land ends beyond the limit of erosion, the work will most likely be undermined or outflanked. Spurs must be formed upstream of the point to be protected, and as they cause erosion upstream of them, each of them requires protection by another upstream of it. This means that the series must be continued indefinitely, and even then is not permanently safe, as the highest of the series is unprotected and liable to destruction, and the others will thereafter in turn be attacked and destroyed. It is only when the most upstream spur can be formed at an inerodible part of the river bank (and such can rarely be found) that the series would be safe. Spurs require constant attention and repairs to maintain them, and the capitalised cost of this would probably be sufficient to pay for the construction of a guide bank (Arts. 182–186), which would not always be liable, like them, to failure, and cause continued anxiety to all responsible for or dependent upon their safety. Moreover, while spurs are being formed much material is wasted, being carried away by the river.

(*b*) *Forms of Spurs.*—The ordinary form of spur consists of a mass of alternate layers of trees and stones, which is capable of sinking unevenly without being broken up; as this settles, additional material is added to it. Seeing that the stone is the only permanent part, the more there is of it the better.

Where stone is not available, spurs have been made thus: at the selected site an abutment is formed by excavating a trench, which is staked and lined with brushwood mats; this is filled with bags of earth crossed in tiers, well trodden and staked, the stakes being braced, and the construction is continued into the current. All the materials being perishable, the life of the structure is not of long duration.

A more elaborate form[1] has proved successful on the Colorado. Round the projecting head of the spurs, and extending well back from it on the upstream side, and for a shorter length on the downstream side, planks were driven close to each other and deeply into the ground to form a continuous sheeting. Other planks were fixed above the bottom row, to which they were spiked, so as to carry the protection above high-flood level, and this upper sheeting was continued to the natural bank, and protected by a horizontal apron of sheet planks. The spur head was stiffened by wales, to which cables were attached and run to anchorage in the spur. Subsequently, as the woodwork was burnt by grass fires, it was replaced by sloping concrete slabs with a horizontal apron, also of slabs protected on the waterside by sheet piling. Apparently it was not necessary to provide against deep scour.

In Egypt spurs are made entirely of loose stone, which yields to settlement. These can easily be increased in section or length as repairs or extensions are required. They are raised about 2 feet above high-flood level at the shore end, and thence slope usually about 5 to 1 down to the river end, which is about 3 feet above low water. The effect of the longitudinal slope is to diminish the violence of the end swirl. The crest width is from 3 to 6 feet, the side and end slopes are 1 to 1, and for a short length the river bank upstream and downstream is revetted to protect the root of the spur from erosion by eddies. An earthen "tie bank" connects the spur with the river embankment, so as to prevent it from being outflanked. Permeable spurs are said to cause silting downstream of them more quickly than impermeable ones, which do not permit of the flow through them of silty water. Such stone spurs are permeable until the silt rises downstream of them, when continued permeability is no longer necessary. In regard to plan, spurs are usually constructed sloping downstream at an angle of about 120° with the current, in order to divert it gently from the river bank. It has been proposed to align them pointing upstream at an angle of 30° with the current, to form still-water pockets in which silt can deposit, because a downstream direction causes embayment below spurs.

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[1] "Controlling the Lower Colorado River," by T. G. Dabney, *The Engineering News*, Vol. LXVI, No. 5, of February 1, 1912, p. 215.

(*c*) *Denehy's Groynes.*—These spurs (Fig. 86) were designed by Mr. P. Denehy for the Narora weir at the head of the Lower Ganges Canal in the United Provinces, India. The head of each spur is formed as a **T** with a cross-piece, about 400 feet long, parallel to the river, of bank heavily faced with stone. This is protected by a stone apron and provided with reserve stone, so that practically it becomes a short length of a Bell bund (Art. 182 (*a*)). This is connected by a cross earthen embankment to the main flood embankment parallel to the river, the whole forming a still-water pocket. The spurs are placed about half a mile apart, with the object of preventing the river making a deep embayment between any pair. It has been found that after the river has cut in about 660 feet it begins to straighten itself. Originally the upstream part of the **T** head was made too short, so that embayments used to cut into the connecting embankment. A short length of the latter near the **T** head was then moved further downstream, forming a "bayonet head." The upstream part of the **T** head was thus made about 300 feet, and the downstream part about 100 feet long.

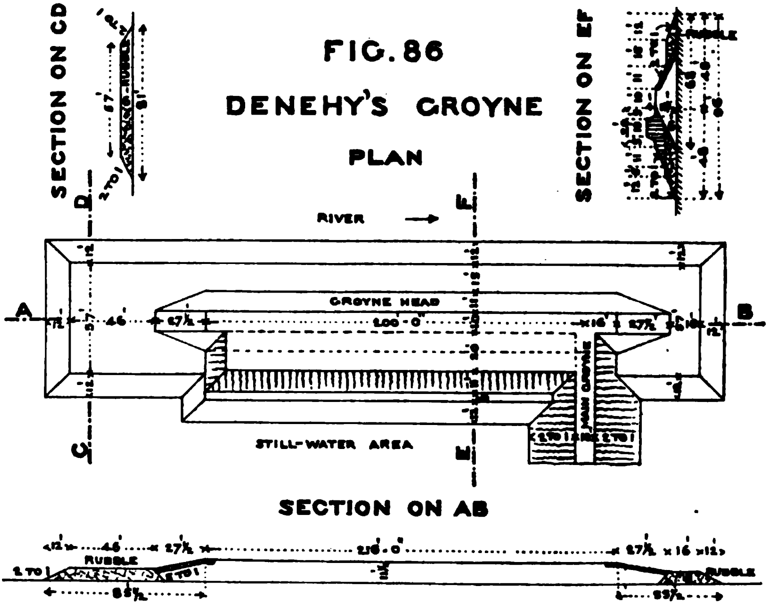

FIG. 86

DENEHY'S GROYNE

The main idea of the design was to economise the cost of protection by forming at intervals short lengths of the Bell bund type, instead of a continuous Bell bund. At Narora these spurs have been successful, although Mr. Denehy admits they are not so permanently secure as the continuous Bell bund. There they probably owe part of their success to the fact that the river is held by the railway bridge works upstream and by an inerodible bluff on the right bank. At Dera Ghazi Khan Denehy's groynes were washed away after a short life by reason of the violent swirls produced by them, whereas the Bell bund downstream, which was constructed many years previously, was uninjured. Mr. Spring recommends that the groyne most upstream should be finished off with an impregnable head (Art. 186). Mr. Denehy considers this would take too much time to construct, and involve much increased expenditure, as, owing to the number of spurs required, they cannot all be made at once, and the uppermost one completed each year would thus have to be formed with such a head. He considers that if his spur is sufficiently armoured at its upstream end it will stand. Further, he thinks his spurs should not be constructed at intervals of less than half a mile, and prefers increasing the intervals to one mile, which would necessitate the retirement of the afflux bund, or river embankment, for a mile to prevent its being injured by embayment.

181. Temporary Training Works.

(*a*) *Brownlow's Weeds.*—These consist of a series of lines, each fastened to an anchor block upstream in the river bed, and supported downstream by a buoy. Trees and brushwood are attached to the lines, and by deadening the current cause silt to be deposited. A spur of any desired length can be formed by increasing the number of the lines. The success of the weeds depends upon the holding of the anchorages, but when once silting commences, the better do they hold.

(*b*) *The Bengal " Bandhal."*—This is a primitive contrivance for causing minor and side channels in silt-carrying rivers to be silted up, so that the main channels may get a concentrated flow down them, which will keep them clear and cause them to scour. This results in the reclamation of their foreshores for cultivation. A bandhal consists of a line of bamboos, up to 50 or 60 feet in length, and from 1 to 3 inches in diameter, worked during low water into and across the bed of the channel to be closed, and fastened together with string at the top to form a temporary fence, which is rendered sufficiently impermeable by fixing mat screens to it. This system foreshadows the more elaborate one, which has been developed in America, and is known there as the "hurdle dyke."

(*c*) *The Hurdle Dyke.*[1]—This construction has been successfully carried out on the Mississippi, and may thus be described (Fig. 87). To prevent erosion of the river bed from undermining the dyke, a flexible mattress is formed on sloping ways, brought on to a platform, carried on special barges, and is lowered on to the bed by being weighted with stone. It is manufactured of wattling brush upon poles, spaced about 5 feet apart, and these are lapped together and fastened by spikes and wire to give the required width. The brush is spiked to the poles at the edge of the mattress and elsewhere at intervals to every third pole. The width of the mattress varies from 60 to 130 feet, according to the depth of the water and the liability to scour. The hurdle consists of a row or parallel rows of piles driven through the mattress at about one-third of its width from its upstream edge, either singly or in clumps, each consisting of three or four piles, the tops of which are drawn together by wire rope to form a sort of pyramidal structure, the piles at river-bed level being from 8 to 10 feet apart. In the improved form, the curtain, or wattling row, is braced at an angle of about 45° by vertical diagonal braces, which are heeled against a row of clumps and securely fastened at top and bottom to the piles against which they abut. The piles vary in length from 25 to 60 feet, and they are driven into the bed for about 15 feet, with the larger end down, by means of a hydraulic jet and weight of about one ton. They are spaced so as to come to about one pile to the lineal foot of the dyke. The tops of the piles are kept about 20 feet above low water, except that of one in each clump of the wattling row, which is 25 feet above that level, in order to catch drift and prevent it from passing the hurdle. The piles of that row are connected along its upstream face by wattling of fine brush or by curtains made of brush; this forms a permeable barrier, through which the silt-laden current passes at a velocity so much reduced that silt is deposited on the river bed upstream and downstream of it, and this forms a foreshore

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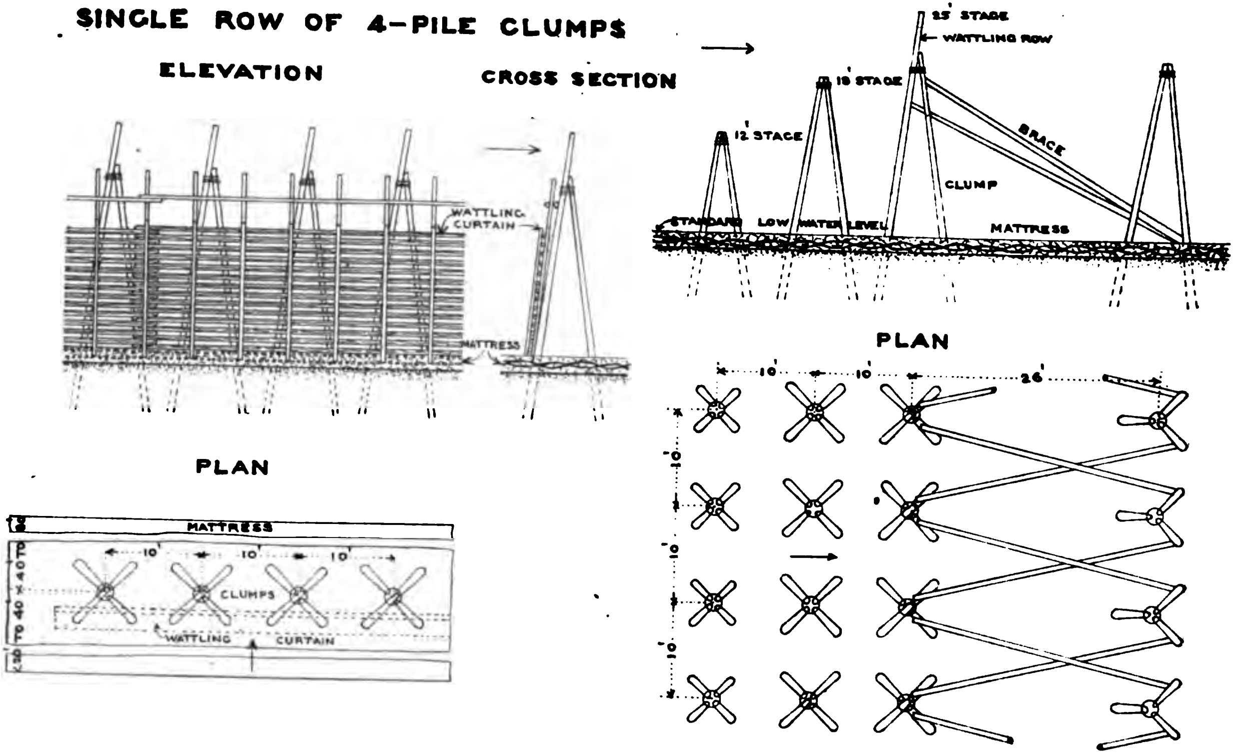
[1] Notes on the Mississippi River, by E. F. Dawson, Thacker, Spink & Co., 1900.

FIG. 87

HURDLE DYKES



SINGLE ROW OF 4-PILE CLUMPS

ELEVATION

CROSS SECTION

PLAN

FOUR ROWS OF 4-PILE CLUMPS

CROSS SECTION

PLAN

projecting for the length of the dyke. After the deposit has reached a sufficient height it can be revetted by rubble stones on its river front, and eventually it gets overgrown with riverain shrubs.

Mr. Dawson constructed three dykes, aggregating 4,650 feet in length, to deflect the Indus at Dera Ghazi Khan, but these were not finished before the river rose, although most strenuous efforts were made to complete them, and were thus unsuccessful. The work was an entirely novel one in India; it was commenced very late in the fair season, difficulties were experienced in getting material, and, unfortunately, the river, instead of rising gradually and steadily, the condition required for silt deposit, fluctuated greatly in level. Eventually a high flood came unusually early in the season and wrecked the dykes. One of short length, however, survived the flood season and produced a small foreshore.

(*d*) *River Improvements.*—In his book Mr. Dawson describes various forms of river bank protection practised on the Mississippi, such as bank revetments, continuous and detached revetments, bank heads, submerged spur dykes formed with cribs; also silt dams to maintain the cross-sections of channels, etc. In most of these works mattresses weighted with stone are used, also, where required, piles, cribs, and stone surfacing.

(*e*) *General Remarks.*—Temporary works for training the low river will generally be washed away during floods, and what the river has previously deposited it can easily remove. Much of the material forming the constructions described above is of a temporary nature, and in India, or where the climatic and other conditions are severe, would have but a short life. Such perishable protection cannot control the river beyond its own existence, and on the termination of that, old conditions would tend to be resumed. Of the materials mentioned, stone is the only permanent one, and its exclusive use for river protection forms one of the leading features of the Bell bund, which is dealt with below. Permanence in such protection is essential if security is to be gained and true economy to be obtained. The Mississippi is probably unique in the value of the riparian interests to be safeguarded. On most alluvial rivers that value is not sufficient to justify works costly both in construction and maintenance.

It is perhaps possible that a permanent hurdle dyke could be made by means of concrete piles[1] which could be formed of sufficient length, and by means of the hydraulic jet could be sunk to sufficient depth. These might have their bases secured by a substantial coating of stone deposited as a bar on the river bed. The superstructure filling might be of temporary wattling, as before, renewed when necessary; probably then only a few feet at the top would have to be replaced. A great advantage of a hurdle dyke, even of a temporary nature, is that it can reclaim a foreshore on which permanent works can most cheaply be constructed. Mr. Molloy[2] seems to object to hurdle dykes as throttlers of the river, but these they would not be were they constructed not to intrude on its final deep channel.

182. Guide Banks—History—Plan.

(*a*) *History.*—In India the original forms of river training at the sites of railway bridges and weirs and a few towns, that are the only points the holding of which has been attempted, took the form of spurs. From these the guide bank was gradually evolved, but was first designed on sound lines by the late Mr. J. R. Bell,[3] and is called a " Bell bund " after him. It has since been elaborated by Mr. (now Sir) Francis J. E. Spring, who has fully discussed in " River Training and Control "[4] the principles involved and the best form of construction. The following description of guide banks is derived from that book, which deals with them in connection with large railway bridges. Certain modifications thereof will be necessary in the case of weirs.

(*b*) *General Plan.*—The principal objects of guide banks are to direct the river in a permanent straight path normal to the main work, and to remove eddies and disturbed water to a safe distance from the flanks of that work. It is therefore generally necessary to construct the banks in pairs, one on each side of the river; the more symmetrical these are in plan in regard to the axis of flow the better, although practical considerations connected with the site sometimes prevent the realisation of the theoretically best plan. If one of the natural banks of the river is hard and inerodible, it will be economical to treat it as a guide bank and construct on the other side only a single artificial one, which in alignment should be symmetrical with that of the natural bank opposite. For railways it is considered necessary to concentrate the protection near the point to be safeguarded, and especially on the upstream side, so that for them very long guide banks are not required. On that side embayment by the river should not be allowed to approach within a furlong of the work to be protected; for this purpose, as a general rule, the guide bank should extend upstream for about one-tenth more than the length of the bridge. On the downstream side swirl holes should not be permitted to form in dangerous proximity to the works, and the guide bank on that side should therefore be made from one-tenth to one-fifth the length of the bridge, according as the flow is moderate or rapid. Where the khâdir, or low-lying area submergible in floods, is very wide, it may be necessary to lengthen the upstream part of the guide bank so as to prevent the river bending round above it, as thus the water would tend to outflank it and attack the railway approach bank or flank embankment of a weir. It may be asked why such banks should not alone be constructed, the guide banks being omitted, and be themselves protected to be secure from attack. The answer (Art. 179 (*b*)) is that such protection would tend to the formation of a deep undermining channel parallel to itself, which would direct the flow of the river along the face of the bridge or weir, and not normally through or over the work.

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[1] Minutes of Proceedings, Inst.C.E., Vol. CL; " Pile Sinking," by E. M. de Burgh; and *Engineering News* of March 26, 1903.

[2] Government of India Technical Paper No. 118, p. 46, para. 39.

[3] Technical Papers No. 2A and No. 2B, by J. R. Bell, M.Inst.C.E., Government of India Central Printing Office, Simla (1887 and 1890).

[4] Technical Paper No. 118, by Mr. F. J. E. Spring, C.I.E., M.Inst.C.E., etc., *ibid.* (1903).

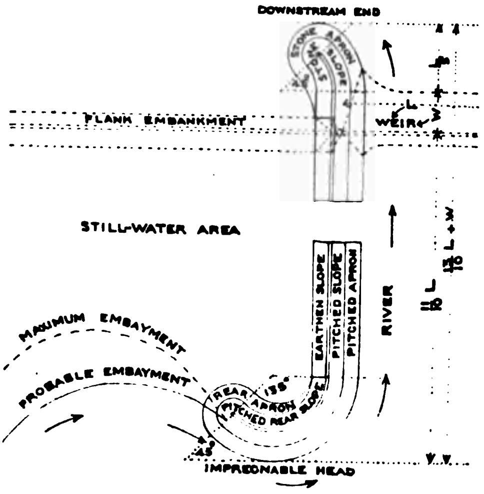
(*c*) *Details of Plan.*—It is essential that swirls (Art. 169) should not be produced along the face of the guide bank, as they cause "extraordinary" erosion (Art. 166 (*a*) (iii)). That face should therefore be made as smooth and regular as possible, and on no account should swirl-producing spurs be constructed projecting from it, although in earlier practice this was erroneously done under the mistaken idea that thereby the guide bank would be protected by diverting the current from it. In order to secure a gentle entrance for the river into the channel between the guide banks these embankments might be slightly curved inland near their heads, but this would involve the widening of the river there, and this might lead to irregular silting of its bed, and possibly to the formation of islands, which would disturb the regularity of the flow approaching the main work. It is better therefore to make the guide banks straight and as nearly as possible normal to that work, although this may cause some disturbance of the river's flow when changing its course at the head of the channel between them. (See also Art. 186 (*d*)).

(*d*) *General Remarks on Guide Banks.*—Care should be taken not to select as a site for the main work one where the river has a tributary or side channel flowing parallel to it, as this may draw off discharge, which will cause the minor channel to enlarge itself and possibly so as to become the main stream when it might outflank the works or at least induce an irregular approach flow to them. The whole plan of the works may have to be changed at the beginning of their construction, as it is necessary to adapt them to the existing conditions of the river in order to facilitate construction, and those conditions may have resulted from changes wrought during the previous flood season. Advantage should be taken of a favourable set of the river, and where practicable this should be induced by reclamation work previously carried out with that object in view.

The essentials for guide banks are: a proper alignment as symmetrical as may be, a sufficient still-water area (Arts. 179 (*b*) and 188), an ample apron (Art. 185), an impregnable head (Art. 186), and a large reserve of stones for repair (Art. 187) during its early years. Fig. 88 is a typical plan and Fig. 89 a typical section of a guide bank.

FIG. 88

PLAN OF GUIDE BANK



Guide banks, in contradistinction to reclamation bunds

(Art. 179 (*c*)), can be regarded as permanent works, which will require but little attention after their complete settlement has taken place.

183. The Embankment of the Guide Bank.

(*a*) *General Remarks.*—The embankment shuts out the river from direct access to the backwater or still-water area (Art. 188), and forms a support to the "slope" (Art. 184) of the guide bank. As it may be subjected to rapid fluctuations of river level, and owing to the afflux of the weir may have to be high, it is essential for safety that it should be most carefully constructed, and that all the precautions noted in Articles 184 to 189 should be taken.

(*b*) *Section.*—The top of the bank should not be less than 10 feet wide (in railway practice it is made from 20 to 30 feet, to allow of the working of material trains, but for irrigation works the width might be reduced if trams are used); its side slopes 2 to 1, and its free-board 4 to 5 feet. In calculating its height due allowance should be made for that, to which the backwater will rise owing to the pocket (Art. 195 (*b*)) formed by the embankments, and also for settlement; the latter, as it may affect the "slope," should be reduced by careful consolidation of the earthwork (Art. 196 (*d*)). The river or upstream slope will be protected by the pitching of the "slope" (Art. 184), but the land or downstream slope, as it will stand in the backwater (Art. 188), and thus be subjected in the flood season to wave-wash, and in the fair season to wind-erosion, also requires protection. If the bank is made of sand, the latter can be guarded against by a facing of good earth not less than 1 foot thick, but it is as well to render the slope more secure against the effect of the former by covering it with a layer of stone, etc., which may be of quarry refuse or old bricks between the interstices of which vegetation will grow and act as additional protection. Wave-lap can also be prevented by fixing along the bank a floating rope (Art. 181 (*a*)), secured at intervals by being tied to posts driven into the bank, and having old sleepers spiked on to it along its length; or live hedges (Art. 198 (*f*)) can be grown in front of the bank.

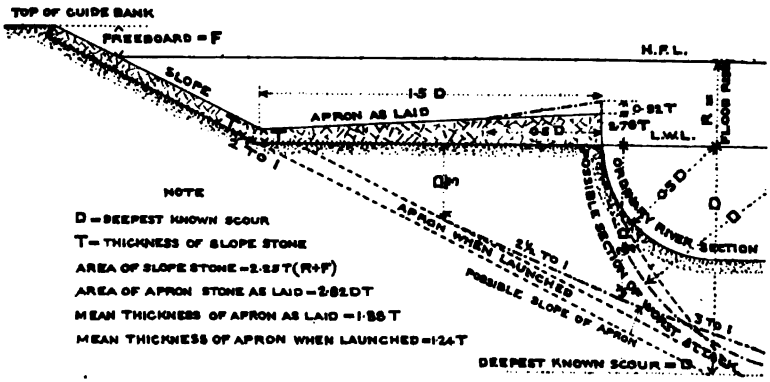
(*c*) *Material.*—The material of which the bank is made should not be taken from borrow pits excavated on its downstream or backwater side, as these may induce percolation through the bank. It should be derived wholly from the excavation for the apron (Art. 185), for which purpose the upstream slope of the bank should be continued down to river low-water level, and the seat for the apron stripped throughout to that level. If the amount of this spoil is in excess, it should be utilised in increasing the section, and particularly the width of the bank.

184. The "Slope" of the Guide Bank.

The "slope" (Fig. 89) is the name given to the part of the pitched surface of the upstream, or river, side of the guide

FIG. 89

GUIDE BANK PROTECTION



bank, which is above river low-water level. It is essential that this slope should not be undermined nor slip, and that, if it commences to give, it is at once made up to proper profile. If the slope were to fail, the embankment in rear would be liable to be cut through as soon as the river rose against it. Thus would be formed a breach through which the water would pour and tend to cause a dangerous embayment downstream of the guide bank, that might not only eat it away, but also the flank embankment of the weir, which work would then be outflanked. The pitching should extend at least to 3 feet above river high-flood level, and should consist of stones, each weighing from 80 to 160 lbs., laid on a layer of quarry spauls, etc., at least 6 inches thick, to protect the embankment from wave-lap through the interstices of the pitching. The pitching has not only to resist the velocity of the river, but has also to prevent the material of the embankment from being disturbed. It has therefore to be increased in thickness for high velocities of the river and fine material in the bank. Mr. Spring, on p. 31 of his book, gives the following table of thicknesses, which apparently include the layer of quarry spauls:

Fall per Mile of River in Inches.	3	9	12	18	24
Sand Classification (Art. 171).	Thickness of Stone Pitching in Inches.				
Very coarse	16	19	22	25	28
Coarse	22	25	28	31	34
Medium	28	31	34	37	40
Fine	34	37	40	43	46
Very fine	40	43	46	49	52

He states that by carefully graduating the stone and keeping the smaller stuff next the embankment the thickness may perhaps be reduced from 6 to 9 inches all round. Further, by carefully hand-packing the stone, it is possible that one-third of the thickness can be saved. This hand-packing can be done in subsequent years, and the stone then removed can be utilised in adding to the apron, where it will always be useful.

185. The "Apron" of the Guide Bank.

(*a*) *Width and Thickness.*—The "apron" (Fig. 89) is the name given to the part of the pitched slope of the upstream, or river, side of the guide bank which is below river low-water level. Being constantly under water, it must be made absolutely proof against any erosion or scour which may attack it. To arrange sufficiently for this it is necessary to ascertain by inspection and sounding of the river in the neighbourhood, as soon as possible after the end of the flood season and before silting takes place, what is the greatest natural bend scour. Owing to the guide bank preventing caving, and consequent silting of the river bed, the "abnormal" scour (Art. 166 (*a*) (ii)) along it will be at a maximum, and should be allowed for by adding a little to the observed natural greatest scour. It is, however, unnecessary to provide for swirl or "extraordinary" scour, for the works should be so designed that this will not be set up. At the upstream head of the guide bank the river attack will be the strongest, and provision should be made there to resist it by increasing the apron. The breadth of the apron as laid during construction should not be less than 1½ times the anticipated depth of scour next to it. The average thickness of the apron pitching when launched should be 1¼ times that of the slope pitching for a gentle and 1½ times for a turbulent river. It should be somewhat increased at the upstream end of the guide bank, where the river attack is most severe, and somewhat reduced at the downstream end where that attack is less (Art. 186 (*c*)). No reduction of the thickness of the apron can be made on account of hand-packing and grading the stones, for such work should not be attempted, as it will be destroyed during the launching of the apron.

(*b*) *Launching.*—This indicates the essential difference between the slope and the apron; the former should never slip, but the latter is intended to slip regularly after its original construction, as it becomes undermined by the river. In order that this slipping of the pitching may take place properly, the apron should be laid on dry ground at low-water level, or as low as possible, so that it may have to drop only the minimum height practicable when undermined. The base for laying the apron should be excavated to that level, and the spoil from it utilised in making up the guide bank embankment. It is wasteful of stone to throw it into deep water to form a slope directly. Further, to ensure the regular and uniform launching of the apron, it is necessary that the stones forming it should subside gradually by being undermined. For this reason the apron is laid with a thickness increasing from the slope of the bank towards the river (Fig. 89), so that at its toe there will be such a weight of stone that it will break down any vertical cliff which may be formed during the erosion of the river bank. Were such a cliff of considerable height to be left standing, the continuity of the slope of the apron would be broken, it would then no longer afford a complete covering of the subaqueous river bank, the whole of the upper pitching might be carried away, and the guide bank itself breached with disastrous results. To guard against such an accident it is imperative that the apron as laid should be wide; a narrow, thick belt of stone is likely to fall *en masse* and to expose an unprotected sand cliff behind it. Individual pitching stones of the proper size are not moved directly by the river; what happens is that they are first attacked by eddies round them, these remove the underlying sand, and then the stone follows. It has been found that the stone at the extreme toe of the apron has thus been rolled from its originally laid position a distance equal to 75 per cent. of the depth of the scour below low water; also, that the average slope which a properly launched apron will assume is about 2 to 1.

(*c*) *River Action on Apron.*—When the current attacks gently the bank on which the apron is laid, it may cause the stone to dribble too far, as it does not directly undermine it and cause it to settle, but scours out a gentle slope down which it can roll. On the other hand, the nearer violent erosive currents approach the bank, the steeper will be its subaqueous slope, and the more liable to settle irregularly. The best condition to secure, if practicable, for successful launching is a moderately quick and not very oblique current against the bank. After the slope has been launched, scour holes may be regarded without fear, provided the settlement they cause is at once made good with additional stone; although their formation should not be encouraged by the design, they will eventually do good by allowing the apron to attain its final settlement. After that has occurred, the guide bank may be regarded as permanent. Until permanency is attained, all settlements should be attended to and any widening necessary effected. Ordinary repairs can best be executed during the low-water season, but dangerous damage during the flood season must at once be made good.

186. "The Impregnable Head."

(*a*) *Principles Involved.*—In Article 169 it has been explained that when the river meets a projection, swirls are produced; in Article 167 (xviii), how embayment takes place at such a projection; and in Article 174, that the river is constantly changing its course by altering its curvature. Now, the upstream end of a guide bank forms a projection tending to cause swirls and embayment, and the logical treatment of it is to form it with a curve which will direct the current gently round it with the minimum amount of disturbance, and, by the permanent embayment it will induce, will fix the course of the river. This is another instance of the advantage of following Nature (Art. 56 (*a*) (iv)). The part of the guide bank immediately downstream of the head will prevent embayment below it, but upstream of the head, where the ground will be soft and unprotected, nothing exists to stop embayment, and it will consequently take place there. The head should therefore be advanced so much upstream that this embayment cannot extend behind it sufficiently far to injure the main work. The sinuosities of the natural river will give an idea of what are the worst conditions of embayment, and the head should accordingly be located so that if these are reproduced at it, there will be at least a furlong of uneroded ground left upstream of the main work. Despite the curvature of the head, the attack of the river will be most pronounced there, and it is accordingly necessary to make the head amply strong to resist any erosive action which may assail it. These are the principles which have led to the design of what Mr. Spring has called the "impregnable head" (Fig. 88, p. 357). This head not only diverts the current round it, but also away from the inland side of the guide bank, so that its inland face does not require to be armoured, except near the head.

(*b*) *Curvature of Head.*—The proper radius to be allowed for the impregnable head depends upon the velocity of the current (which is governed by the gradient of the river), and the probable amount of scour (which is contingent on the nature of the sand of the bed). Mr. Spring, on page 153 of his book, gives the following table of radii to be adopted for the upstream head:

Sand Classification (Art. 171 (vi)).	Probable Maximum Abnormal Scour (Art. 166 (ii)).	Fall per Mile of River in Inches.				
		3	6	9	12	18
		Radius of Upstream Curved End in Feet.				
Very coarse	Under 20 feet	200	250	300	350	400
,,	Over ,,	250	310	375	440	500
Coarse	Under 30 feet	300	360	425	490	550
,,	Over ,,	350	430	510	590	670
Medium	Under 40 feet	400	425	550	625	700
,,	Over ,,	450	550	650	750	850
Fine	Under 50 feet	500	590	675	760	850
,,	Over ,,	600	725	825	925	1,020
Very fine	Under 60 feet	600	700	800	900	1,000
,,	Over ,,	800	900	1,000	1,100	1,200
Radius of downstream curved end of guide bank.		Half the above, with for minimum radius that on which maintenance trains can be shunted.				

Large curvature produces less area of dead water, and therefore smaller swirls. The gradient of the river in its ordinary lengths may vary in accordance with changes of its course, so that, when designing an ordinary protective work, the worst condition (i.e. the highest gradient of the channel in the neighbourhood) should be assumed. In the case of guide banks for a weir the gradient is, however, fixed by the crest of that work.

(*c*) *General Design of Heads.*—The upstream curve should be carried 120° to 140° round the back to secure the protection of the inland side of the earthen embankment of the guide bank; the pitched apron and slope should be continued throughout this back curve, and should gradually die out downstream of it. The curve of the downstream end of the guide bank need be only a short one; the object of this end is to direct swirls away downstream of and to a safe distance from the main work. The ends of the guide bank should be made full height, and there, the better to resist the attack of the river, the thickness of the pitching should be increased by 25 per cent., and the width of the apron as laid should be 2 instead of 1½ times the greatest depth of scour. Mr. Spring considers that the most upstream of Denehy's groynes (Art. 180 (*c*)) should have its upstream end formed as a curved impregnable head, and that had the one at Dera Ghazi Khan been thus constructed, it would have resisted the violence of the river (Art. 180 (*c*) at end).

(*d*) *General Curvature of Guide Bank.*—Mr. Spring prefers giving a gentle curvature in plan throughout the length of the guide bank, so that all of it may deflect tangentially the attack of the worst embayment current, viz., one parallel instead of normal to the main work, and thus lessen the chance of development of extraordinary scour. Other engineers are in favour of a straight guide bank, which will be exposed to the most severe action at a definite known point, its impregnable head, which can be designed extra strong to meet it, while the rest of the guide bank is not likely to be stressed by the river. Reserve stone for the maintenance of the head can be stacked close to it; such stone need not be provided in large quantity all along the guide bank so as to be ready for an attack anywhere in its length, as this is not likely to occur. (See also Art. 182 (*c*).)

187. Pitching Stone for the Guide Bank.

When selecting stone for pitching it should be remembered that it is its submerged weight which is effective, and therefore material of high specific gravity should be preferred; also that heavy stone will launch better than light, and that rough, angular stones will interlock with each other better than smooth, regular-shaped ones. The stone should be graduated to lessen the amount of interstices which allow of wave-lap.

During the early years of a guide bank a considerable amount of settlement of the apron may be expected, and this has to be made good by additions of fresh stone. For this purpose at the start a large reserve of stone should be stacked on the guide bank, or arrangements made for bringing it at once by train. In the latter case the curves of the approach lines should be such that a train can easily be shunted on them. The cross-sections of the apron should be taken yearly by sounding as soon as the flood season is over, and all additional stone required should be placed on it then, as that is the best time for repairs. If, however, emergent repairs have to be carried out in the flood season, the stone should be distributed over the defective part of the apron as evenly as possible by being deposited from boats moored to the guide bank. On no account must the undermining of the apron be allowed to extend so as to carry the upper slope with it.

188. The Backwater Area of the Guide Bank.

Owing to the facts that the construction of a weir raises the high-flood level of the river by an amount equal to the sum of its own height and the afflux produced by it, less the original natural flood height, and that the slope of the country inland is downwards, retired flood embankments, one on each bank, are necessary complements to guide banks unless natural bluffs take their place. The area between the two retired embankments parallel to the river and bounded by the flank embankments of the weir normal to the river forms the backwater. It is necessary that this should be a " still-water area," so as to lessen the embaying action of the river, particularly at the head of the guide bank (Art. 179 (*b*)). No parallel nor cross-currents should be allowed to take place in it, as these may increase that embaying action and possibly make the river cross the weir askew ; this would diminish the discharging capacity of the work, and cause danger by producing scouring cross-currents upstream and downstream of it. To prevent such cross-currents forming, all side channels should be blocked (Art. 179 (*a*)), and the whole backwater area should be silted up as quickly as possible. To effect this silting small inlets and outlets should be arranged for, so that they will not increase in size. They will thus allow only a very slow-moving current in the backwater, which will deposit silt at the maximum rate. The outlet, which will be at the downstream end, should therefore be formed as a controllable sluice through the guide bank, and should have an inerodible invert, or pavement, to prevent its bed from deepening and forming a scouring channel, which might eventually cause embayment of the river. When the area has silted to ordinary flood level, it will get covered with riverain vegetation, which will effectually prevent wave-wash of the retired embankments and inland side of the guide banks.

While the foreshores of the backwater area should be induced to silt, it is necessary to keep the river channel clear and free from islands, which would mask the flow over the weir crest and make it irregular. When such islands do form, they also, if unattended to, will get covered with vegetation, which will protect them from erosion. As a remedy the vegetation should be cut down, the surface ploughed, and channels excavated through the islands parallel to the river's flow to induce it to scour (Art. 168 (vii)). The formation of islands is evidence that the length of the weir (which may be necessary for passing off maximum floods) is too great for the ordinary flow, and that is thus reduced in velocity through the backwater.

189. Construction of the Guide Bank.

The construction of the guide bank should be commenced from the abutment, that is the weir, and should proceed regularly upstream. If its completion cannot be achieved in one season, the reduced length commenced should be finished off and should have a temporary impregnable head formed at its upstream end, so that it may hold the river, and not be outflanked by an embayment. In the subsequent season this head should be removed and the guide bank similarly continued or completed. To ensure rapid progress, proper and early supplies of stones should be arranged for, and it will facilitate work if these can be brought to site by trains.

The slope and the apron should be built between templates 100 feet apart. In Article 185 the construction of the apron in the dry has been described, but this may not always be possible, and part of it may unavoidably have to be formed in deep water. When this is the case, the quantity of stone required for the subaqueous part of the apron should be calculated; this amount should be carefully and regularly dropped into the water from boats and precautions should be taken at first not to extend the apron too far so that it will be undermined and the material wasted.

In the most difficult case a length of the entire guide bank, including the embankment, may have to be formed across a deep-water area. If possible, that area should be temporarily reclaimed by silting it up; but if this is not feasible, the apron should be formed in advance and gradually built up above water level, after which the superstructure can be constructed in still water—this involves a very large expenditure of stone.

The cost of railway bridge guide banks has varied from Rs. 75 to Rs. 180 (£15 to £12) per foot run. Those for the Sárá Bridge across the lower Ganges, where the depth was excessive and the sand of the river very fine, were estimated to cost Rs. 475 (£32) per foot run. The cost depends greatly on the price of the stone, and that is due principally to the length of its lead and nature of its haulage. The extent of the sectional area of the protection also affects the cost.

190. Observations on Guide Banks.

(*a*) *Guide Banks for Weirs.*—In Article 175 (ii) and (iii) it has been pointed out that whereas a railway bridge may not produce an afflux in the river, a weir certainly will; that will take place to the amount indicated in Article 188. This afflux will extend throughout the backwater, and will probably cause the river to top its banks in high flood. To prevent this from doing damage the safest precaution to take is to construct the guide banks for the whole length of the backwater; this being considerable, the cost will be great. With good retired flood embankments and proper measures for reclamation (Art. 179 (*a*) to (*c*)), it should, however, be quite safe greatly to lessen the length of the guide banks and upstream of them to construct Denehy's groynes with spur heads, say, 500 feet long and spaced 1 mile apart clear, and to a regular tortuous alignment in the general plan of the series. The upstream ends of the shortened guide banks and of the Denehy groynes most upstream should be made with impregnable heads. While the afflux of the weir is a source of danger, it is also a moderator of the violence of the river by reducing its gradient, and, moreover, tends to cause the backwater area to silt up, so that the proposed system should afford ample protection. Were it to prove insufficient, there would be time to extend the heads of the groynes, and eventually, if necessary, so as to form a continuous guide bank. The construction of the weir will cause the bed of the river to silt up, and thus will reduce the length of the apron. It will lead to an increase of the length of the carefully-laid "slope" at the expense of the roughly-laid apron. By keeping the undersluices open during canal closures a considerable width of the apron can be repaired in the dry.

(*b*) *Pitching of the Slope.*—In Article 184 it was stated how the thickness of the pitching of the slope noted in the table there given might be reduced by gradation of the stone and hand-packing. A still greater reduction could be effected if the pitching were carefully laid, as is done in the case of a high earthen dam (Art. 91 (*c*)), where the stones are subjected to equally violent action by greater wave-wash. Mr. Bell was evidently struck by this form of pitching when it was brought to his notice, and considered it " a perfect and yet simple solution of a difficult problem."[1] As wave-lap washes out a sand embankment so quickly, such pitching for the slope of the guide bank should be underlain by at least 9 inches of quarry spauls, etc. Similar pitching is, of course, not practicable for the apron, as that cannot be hand-laid.

(*c*) *The Apron.*—Mr. Spring estimates that the final slope which the apron will assume after complete settlement will be 2 to 1 throughout. If it extends to a great depth, it seems probable that the slope will not be uniform throughout, but will get flatter and flatter at its base as shown by the chain-dotted line in Fig. 89, p. 359. This being the case, its length will be somewhat increased.

To provide for this extra length, and to ensure that the extreme toe will break down any cliff that may be formed initially during the erosion of the underlying sandy soil, it would appear advisable slightly to increase the thickness of the pitching there as shown by the chain-dotted lines in Fig. 89. After the toe has been properly launched, it is probable that the rest of the pitching will follow it regularly. The largest stones should be reserved for the toe, so that they may not dribble away too far.

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[1] Minutes of Proceedings, Inst.C.E., Vol. CXXXII, p. 238.

In order that the interstices of the pitching may be completely filled, so as to protect the river bank from wave-lap and erosion, it would seem expedient to mix smaller insoluble material with the apron stones as they are being stacked, so that this may automatically be distributed throughout the pitching during launching and settlement.

CHAPTER XIV.

EMBANKMENTS FOR LARGE RIVERS IN ALLUVIAL SOIL.

191. General Remarks on River Embankments.

(*a*) *Necessity for Cultivation.*—In Article 162 (*c*) it has been stated that one of the leading features of an Indian alluvial river is the insufficiency of its channel to contain its flood water. In Article 177 (*c*) the opinion has been expressed that it is undesirable for man to prevent high floods from submerging the newly and rapidly forming deltaic lands of such a river. The question will now be discussed whether it is, or is not, advisable for embankments to be constructed to shut out floods from the riparian land of the upper river where the ground has already been formed and is being raised only very slowly. The primary effect of such embankments is to prevent water from spilling over the country, but this increases the flood discharge of the entire river downstream of them unless relief is given by escape channels. The primary object of embankments is generally to protect property, chiefly land, from submergence, but there are cases, such as the Mississippi and the Danube, where these works were constructed in order to improve navigation of the rivers by concentrating the flood discharge so as to scour out deep navigable channels. It is evident that if the surface of the country is liable to be inundated during the cultivating season at more or less uncertain dates, for periods of indefinite duration and for unknown depths, the risk of damage to the crops will be so great that it will not be wise to attempt to raise them. Moreover, the river floods traversing such an area wonld concentrate themselves along defined lines, and would thus scour out flood channels or cover the land with sand, which might render cultivation difficult. Further, although crops would perish under natural conditions, hardy riparian vegetation adapted to them would flourish and prove another obstacle to cultivation. When, however, the floods are confined by embankments, all this damage is prevented, and the river at flood level supplies irrigation water most conveniently to the protected lands.

(*b*) *Improvement of Navigation.*—In respect to navigation Mr. Dawson [1] arrives at the following conclusions:

> (i) "The general effect of the construction of levees" (embankments) "along the banks of a river is to improve its regimen, to deepen its bars, to level up its pools, and to increase the widths between banks—all tending to enable the river to discharge more of its water through its own channel. (Of course, during the progress of confinement by levees, the high stages of floods rise till a maximum due to confinement is reached.)"
>
> (ii) "After completion of the Levee System, and during the approach of the river to its final state of equilibrium of bed and channel, the levels of low, medium, and high-stage waters are lowered, till, what may be called, 'final' stages of each are reached."

American engineers hold that the levees concentrate the flood discharge, and thus scour out the channel which will afterwards be followed by the low-water stream, and remove the bars which are the principal obstacles to navigation. (See also Art. 179 (*a*).) It is said that the leveed portions of the Mississippi have a superior channel to the un-leveed parts.

Some authorities recommend dredging instead of embanking as the proper course to take with alluvial rivers. Whatever may be practicable elsewhere, dredging is not financially possible on the silt-charged rivers of India, which have friable banks and riparian land of small value.

(*c*) *Advantages Immediate and Prospective.*—Among rivers which have been embanked are the Mississippi, the Po and Rhine in Europe, the Yellow River and others in China, the Northern India rivers, and the deltas of Bengal and Madras. General benefit may be said to have resulted by thus meeting immediate requirements; the question for consideration is whether that has been secured permanently and without risk to future interests.

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[1] "Notes on the Mississippi River," p. 99.

192. Objections to River Embankments.

(*a*) *Objections Raised.*—The following objections to river embankments have been stated:

- (i) They interfere with the river's natural operations in raising the country generally;
- (ii) They deprive the protected land of much fertilising silt;
- (iii) By shutting off inundation water they cause the protected land to deteriorate by the rise of subsoil salts;
- (iv) They cause the river bed to be raised by silt;
- (v) They raise the river high-flood level;
- (vi) They cause the river, by changing its course, to erode its cultivable banks and to throw up sterile sand banks.

Of these objections Nos. (i), (ii), and (iii) refer to damage to surface conditions and thus to cultivation, and Nos. (iv), (v), and (vi) to detriment to the natural regime of the river. They are dealt with shortly below.

(*b*) *Damage to Cultivation.*—The general raising of the country by silt deposited by the river (i) has been described in Article 162 (*c*). A continuous line of embankments across all spill channels, by shutting off the river floods, prevents this action taking place inland of them, and confines the raising to the riparian land inside of them, which will thus probably rise higher than it would do if unconfined. It is believed that the valley of the Nile during historic periods has been raised only at the rate of 4 inches a century. Although this river has a comparatively small amount of silt, being greatly due to the overflow of large lakes, yet with an ordinary alluvial river even the accelerated rate of rise will be slow. Probably the most marked effect of embankments in this respect will be the quickened increase of the delta due to the diminished deposit of silt upstream of it on the country generally.

Objections (ii) and (iii) apply chiefly to un-irrigated land, as irrigation by silty water will bring sufficient manurial matter on to the land to maintain its fertility. It will also tend to raise it slowly and wash out deleterious salts.

(*c*) *Detriment to River Regime.*—The raising of the river bed by silt, (iv), said to be due to the construction of river embankments, is disputed by some engineers, who hold, on the contrary, that the bed is thereby lowered by increased scour Art. 191 (*b*)). It seems probable that the bed must be raised as the delta progresses seawards, but it is quite possible that the amount of its raising may be less than that of the confined riparian land, which, although it receives per unit of area less silty water than is carried in the river channel, unlike it is practically not subjected to scour. Thus the bed does not rise nearer to the surface of the country.

Every one admits that the embankments, by preventing spill, increase the high-flood discharge of the river, but many state that when a settled regime has been attained, the high-flood level is not raised, (v), as the river adjusts its level by increased scour and widening by erosion. So many causes affect the high-flood level (Art. 176) that it is difficult to say which of the two opinions is correct, more especially as it is improbable that sufficient time has yet elapsed for an embanked river to have attained its final regime. However, in places the flood level does increase as the embankment system is developed, and therefore the banks there have to be raised from time to time to keep pace with that increase. Possibly at these places the river bed is sufficiently hard to resist scour, and has therefore not been deepened thereby.

Erosion, (vi), is the principal objection raised, as it affects cultivation immediately (Art. 166 (*d*)). In Sind, before the recent large development of embankments, babhul trees from 8 to 14 feet in girth grew on the river margin, indicating a permanence of at least sixty years. Now there are not any riparian forests over twenty years old. American engineers admit that caving chiefly occurs in the central leveed part of the Mississippi, but it is not known what happened there before the embankments were raised. Mr. Dawson[1] notes that the greatest amount of caving takes place when the river is in its middle stage, i.e. when it is flowing between its banks, and not when it is in its high stage overflowing them. The question has been put in America, " How, then, can the levees affect or influence the amount of bank erosion ? " but does not appear to have been answered there ; a possibly correct reply is given below.

(*d*) *Effect of Embankments on River Regime.*—Fig. 90 is a diagram to illustrate what seems to be the probable effect of embanking a deltaic river in a rainless area. AB, CD is the river in a state of nature—unembanked; thus its floods escape over its banks, and its flood discharge gets smaller and smaller as it proceeds to the sea. If the river is in a rainy area, the discharge is affected by the inflow of tributaries, but the conditions arising from side spill are unaltered. The result is that the river acquires gradients which suit its diminished discharge from point to point. Assume that thereafter the river is completely enclosed on each side by flood embankments, EF and GH, so that all spill is prevented; it then becomes AB′, CD′, with a flood discharge at B′D′, practically equal to that at AC. The lower reaches which, owing to their diminished discharge, had originally adjusted themselves to comparatively steep falls, are no longer able to maintain their courses unchanged on account of their artificially increased discharge. The river therefore has to reduce its gradients between the fixed levels at the head and the tail (the sea) in the only way practicable, i.e. by lengthening its course to the sinuous one shown in the diagram, and this leads to erosion. Mr. Molloy[1] considers that the flood discharge of the Upper Indus has been increased at least 50 per cent. by embankments, and states: "This increased flood discharge, as might naturally be supposed, would require a higher ratio of tortuosity than was the average before the levees were commenced." He adds that the tortuosity has been reduced by severe retrogression of levels (the deepening of the flood channel), which is also a result of the system of embankments.

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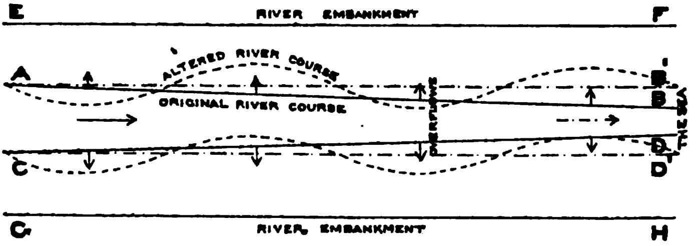
[1] " Notes on the Mississippi River," p. 60.

FIG. 90

EFFECT OF RIVER EMBANKMENT



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[1] Government of India Technical Paper No. 118, para. 20, p. 15.

This scouring out of the flood channel causes the river to impinge at altered angles against its banks. While the banks are supported by the flood water up to their tops, they are able to resist the erosive action; but as the river surface falls below them (Art. 167 (x) and (xi)), that action is able to erode the sodden banks as the altered direction of the current is still maintained. This is the explanation offered of the effect noticed on the Mississippi of levees (river embankments) producing increased caving, although that does not take place until after the high-flood stage has ceased.

193. System of Retired Embankments.

(*a*) *General Remarks.*—If it is accepted that the conditions of the unembanked river are unsuited to cultivation (Art. 191 (*a*)), and that the closely embanked river is prejudicial to certain riparian interests, although greatly beneficial to others (Art. 192), it should be seen if a *viâ media* cannot be found so as to secure the maximum advantage with the minimum disadvantage. It is thought that the system of retired embankments is the solution of the problem. The existing system of embankments close to the river has gradually been developed from the small ring banks raised by cultivators to protect their crops from inundation—these were gradually raised and extended so as to become continuous for miles. Their original purpose was to safeguard individual interests, and their effect on the general regime of the river was then never considered. Not only were the banks advanced as near to the river as safety permitted, but the cultivation followed close on to them. Thus when the time came for engineers to maintain the line of embankment, they found works already constructed and existing interests to be conserved, so that a new departure seemed out of the question. It is natural that considerations of cost mainly influenced them, as it is probable that at first the consequent effect on the river of artificially increasing its flood discharge was not realised. Unfortunately, the gentle downward slope of the country inland from the river (Art. 162 (*c*)) makes the near embankments cheaper and safer than those constructed more inland, while the latter also have the disadvantage of surrendering cultivated land to submergence by inundation. The near embankments are, however, from their position very liable to destruction. In Sind, in 1912, nearly 30 miles of important loop embankments were under construction or over 6 per cent. of the entire length of embankment. At places of violent erosion it is no uncommon sight to see the ruins of several banks, parts of which have from time to time been carried away by the devouring river. Cases have been known where the river has cut away the sites of designed loops before the works could be constructed. Not only do the banks thus suffer, but the inland country may do so also, as an extensive breach may lead to the inundation of many square miles of cultivation, and possibly to permanent damage by the formation of scour channels traversing the area irregularly. It is often difficult to predict what will be the new course of the river, and still more difficult to foresee what further changes will result therefrom. In Article 162 (*e*) it was stated that there are, however, limits beyond which the river has never been known to travel, and, as far as practicable, it seems desirable to select the neighbourhood of these limits for a system of retired embankments which will most likely have a long life, even if they are not absolutely permanent, and this will justify the increased capital expenditure on them. Moreover, if the enlarged riverain area inside these retired embankments is not suitable to post-inundation cultivation, it can be utilised for establishing riparian forests, which will benefit from the annual inundation.

(*b*) *The Advantages and Disadvantages of Retirement.*—The following are advantages gained by retirement of embankments:

(i) The minimum interference with the natural operation of the river in raising the country by silt deposit;
(ii) The maintenance of a large river reservoir capacity;
(iii) The filling of this reservoir will reduce the "peak" of the high flood;
(iv) The emptying of this reservoir will longer maintain the river at good irrigating level;
(v) It may be practicable to utilise such a reservoir so as to give temporary storage of water for canals when the river level falls;
(vi) The reduction of the high-flood level will preserve the regime of the river, and thus will diminish the erosion of good land and the throwing up of sterile sand banks;

(vii) The longer life of the embankments will permit of their being constructed carefully and slowly, well in advance of the period when the river will approach them, and thus will give time for their self-consolidation by settlement;

(viii) This longer life will afford greater permanence to irrigation interests, and thus conduce to the attainment of that sense of security which is essential to progress.

The following are disadvantages attending the retirement of embankments:

(ix) Increased cost. Against this must be set the saving of replacement of embankments by retired loops and the loss of crops on eroded and inundated areas.

(x) Lessened safety. The retired embankments will seldom be of great height, and it should not be difficult to construct them securely, while owing to the lower level of the ground it should be easy to wet their bases well in advance of the advent of high floods.

(xi) Increased length of open canal head. As the embankment is retired from the river, so will the length of the open canal head between the two be increased. Not being protected from floods, it is particularly exposed to silting. A remedy for this would probably be silt regulators (Art. 204 (*d*)).

(xii) Reduction of the cultivated area. Generally it will be possible to grow on the riverain area post-inundation crops, such as wheat, instead of rice, and where this is not practicable, forests might be planted.

The advantages of retirement outweigh the disadvantages, and indicate the desirability of constructing embankments well away from the edge of the river. By adding reclamation bunds (Art. 179) to the retired embankments, the latter can be made safer by the silting thus induced, which will tend to produce along them foreshores free from scour channels, and thus rendered more suitable for post-inundation cultivation or forest plantations. If is carried out a proper system of such reclamation, thereafter the bunds can be enlarged to river cross embankments, with their heads projecting to a general, regular, sinuous alignment, and, if necessary, finished off with Denehy groynes (Art. 180 (*c*)). It may thus be possible to secure greatly increased permanence for the course of the river, and to render remote the chance of destruction of the main embankment line.

194. Projects for Retired Loop Embankments.

(*a*) *General Remarks.*—When an embankment is threatened with erosion by the river, a retired " loop " embankment has to be constructed to prevent the spill of floods from inundating the previously protected area, as the cost of protection by guide banks is prohibitive. As in the case of other projects (Art. 57 (*a*)), the alignment of the proposed loop should first be examined and surveyed, and a preliminary report and estimate submitted. After the proposals have been approved or modified, a detailed project should be prepared accordingly for final sanction. Unfortunately, but little time is available for this procedure, as the works have generally to be designed with reference to the most recent river changes, and carried out between two successive inundations.

(*b*) *The Preliminary Report.*—The report should discuss the general features of the proposal and the reasons for recommending the selected alignment of the loop, which should have a retirement sufficient to ensure a probable life for many years, unless the cost is prohibitive. If alternative lines are proposed for the loop, the reasons for or against each should be stated, and the approximate costs of each should be entered in the general plan against its line. Reasons should be given against any other alignment, which at first sight may appear to be, but is not really, suitable. It should be noted if the culturable area between the loop and the river can be grown with post-inundation crops or otherwise utilised, e.g. for establishing forests.

(*c*) *The Index Plan.*—This should be to the scale of 1 inch to 1 mile, and should be submitted in fair. On it should be shown—

(i) The recent courses of the river (both banks) for at least five years; these to be drawn and dated in distinctive colours. The drawing should extend for a sufficient number of miles upstream and downstream of the threatened portion of the embankment so as to include the whole of the adjacent main curves of the river.

(ii) The existing embankment to be shown in green, and the proposed new loops in red.

(iii) Existing natural features, such as villages, roads, railways, scour channels, backwaters, main canals, etc., to be shown in black.

(*d*) *The General Plan.*—This should be to the scale of 4 inches to 1 mile, and should be submitted in fair. It should extend for about a mile beyond the ends of the proposed loop, and on it should be shown—

(i) Recent river courses of the bank concerned, existing embankment lines, and the proposed new loop (as in (*c*) (i) and (ii) above). Also erosion lines with their lengths dimensioned.

(ii) All principal works proposed in connection with the loop in vermilion (heavy lines).

(iii) Natural features, as in (*c*) (iii) above, and in addition all existing regulators, main sluices, and water-courses, etc., in black.

(iv) Contours of the ground from the river bank to 1 mile beyond the most inland proposed loop, so that the best alignment for this can be seen. The contours to be sufficiently numerous to indicate the nature of the ground surface and to be shown in crimson lake (fine lines).

(v) Cultivated land within the contoured area. The approximate areas in acres of the main separate cultivated blocks should be shown on them. Areas and figures to be in green.

(*e*) *The Longitudinal Section.*—This should be prepared in rough on paper to the scales—horizontal, 4 inches to 1 mile; vertical, 1 inch to 10 feet. The nature of the soil should be described on it, and a note added as to the length of lead of suitable earth for the construction of the loop. A typical cross-section should be given.

(*f*) *The Estimate.*—This should be made out in rough, but need not be submitted. Its amount should, however, be mentioned in the report and entered on the general plan.

The earthwork should be estimated in fair detail, provision allowed for filling in borrow pits, etc., and rates should be fair average ones. Lump sum allowances should be made for all sub-works, and 10 per cent. should be provided for contingencies.

(*g*) *The Final Project.*—After orders have been received on the preliminary project, the final one should be prepared in detail and in accordance therewith; for it the previously submitted index and general plans can be utilised.

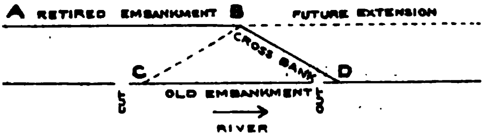
195. Design of Embankments.

(*a*) *General Requirements.*—A river embankment should be raised high enough to prevent its being overtopped by an extreme flood; should have a thoroughly consolidated section sufficient to prevent percolation water from causing it to slip; should have a width of base able to support the superstructure, and to prevent creep of water under it, with, where necessary, a key trench to assist in resisting this; and should have its slopes protected from guttering by rain and erosion by wind and wave-lap.

(*b*) *Alignment.*—The general alignment of embankments has been discussed in Article 193 (*a*). A few particulars to be attended to in the detailed alignment are noticed here. To reduce the cost and increase safety the highest land practicable should be selected, but care should be taken not to traverse, if possible, ground which is sandy, friable, or impregnated with salts, much cracked, or intersected by numerous channels, or irregular in longitudinal or cross-section, as this will lead to differences in settlement. The neighbourhood of villages should be avoided, as their presence increases trespass by traffic.

FIG. 91

DIAGRAM OF POCKET



When an embankment is likely to be breached by erosion of the river, and a retired alignment is decided on, which it may be necessary to extend hereafter, it will be necessary to join the end of the new bank AB to the old line CD by a cross-bank. Care should be taken (*vide* Fig. 91) that this cross-bank has a downstream direction, BD, and not an upstream one, BC, for the latter will form what is known as a "pocket." When the old bank is breached and flood water is thus admitted to the new bank, it will in the latter case pond up at B to the level of the river opposite the cut, C, but in the former one the water will rise at B only to the level of the river opposite to it.

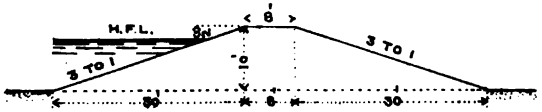
(*c*) *Section.*—The proper section depends upon the height of the bank, the nature of its material and foundation, and the way in which it is to be formed. Of these the last named is the only condition which can be varied, and probably this accounts for the great difference in the section adopted. In Italy the Po embankments have top-widths varying from 16 to 26 feet, side slopes of either 2 to 1 or 3 to 1, and usually two berms on the land side. On the Rhine the embankments have a top-width of only 6 or 7 feet, which is doubled when a roadway is carried, and the side slopes are 3 to 1. On the Nile in Lower Egypt the embankment sections vary thus as the high-flood depth against them increases from about 1 to 7 feet—top-width 10 feet to 16 feet, free-board 3 to 4 feet, both side slopes 2 to 1. A berm 5 feet wide is added on the land side when the high-flood depth is 7 feet, and another similar one when that depth is greater. There the embankments are roughly thrown up and not consolidated.

On the Mississippi a standard section of levee (embankment), Fig. 92, has a top-width of 8 feet, a free-board of 2 feet (one 3 feet or higher is advocated), and both side slopes 3 to 1. Where the bank is 12 feet or more high, a "banquette" (berm) is added on the land side, starting from 8 feet below crest,

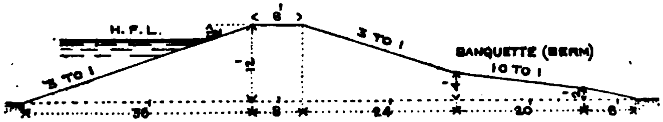
FIG. 92

AMERICAN LEVEE SECTIONS

TEN FOOT LEVEE



TWELVE FOOT LEVEE



and having a top-slope of 1 in 10; for a bank 12 feet high the banquette on the land side has a top-width of 20 feet and rear slope of 1 in 4; for a bank 20 feet high, the dimensions are 40 feet and 1 in 5; for banks of other heights, in proportion. Settlement is assumed to be one-tenth the height, and the banks are set out to allow for it.

In Sind the top-widths vary from 6 feet (for low banks and good soil) to 10 feet (for high banks and sand); the river slope from 3 to 4, or even 5 to 1, and the land slope from 2 to 3 to 1. The free-board aimed at is 4 feet, often it is only 2 feet, but is raised as funds permit. The causes tending to increase the high-flood level (Art. 176) should be borne in mind, and a higher free-board should be allowed where they will probably come into operation.

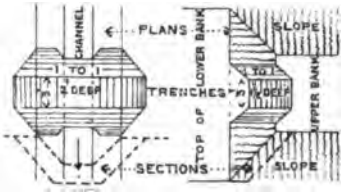
Where the ground is likely to give under the bank, the base should be widened so as to gain the necessary amount of support. Where wave-wash may be expected the river side slope should be flattened, and where the material is unreliable, both slopes should be increased. The top of the bank should be given a slight slope for drainage to the land side, so as to diminish the tendency of the river slope to gutter during rainfall, as rain scores will aid wave-wash in damaging that slope.

(*d*) *The Key Trench.*—This is really a small puddle trench—in America it is known as a "muck ditch." Inspection of river banks will show that owing to the absence of pressure and the effects of the weather a surface soil is generally more porous and fissured than a subsoil of similar material. Moreover, when water meets two dissimilar materials, such as made earth and natural soil, it has a tendency to collect at their junction and to endeavour to pass along it (Art. 79 (*b*)). The key trench meets these conditions as it unites the body of the embankment to the subsoil, destroys the continuity of the base plane and secures the thorough examination of the part of the base it occupies, and the removal from it of vegetation, roots, and rubbish. The failure of levees in America and the occurrence of leaks in Sind have been attributed to the absence of key trenches. A key trench is most important where the ground is porous or sandy, or is cracked and traversed by fissures or by watercourses, etc. Its section will depend upon the high-flood depth against the embankment, the nature of the subsoil, and the importance of the embankment. As ordinary limits its bottom-width may vary from 4 to 6 feet, its depth from 3 to 5 feet, and its side slopes from ½ to 1 to 1. A water-tight foundation is essentially necessary for an ordinary hydraulic work.

(*e*) *Slip Trenches.*—Wherever there is an abrupt change in the level of the ground, or of the top of the embankment under construction, one or more slip trenches (Fig. 93) should be made so as to form junction dowels to prevent the creep of water along the junction plane of the earthwork. They may have a bottom-width of 3 or 4 feet, a depth of from 1½ to 2 feet, and side slopes of 1 to 1. Their sides and those of the irregularity being dealt with should be sloped so that the embankment during settlement may settle tightly against them. The less the nature of the soil is able to withstand percolation, the more numerous and the larger should be the slip trenches.

FIG. 93

SLIP TRENCHES



CHAN^{t} CROSSING BANK JUNCTION

(*f*) *Sand Cores.*—When the embankment is likely to leak owing to the nature of its material, and good clayey soil is not procurable, a sand core should be made to prevent the formation of a large leak by the property the sand possesses of settling when moist into a compact mass. The core should extend from the base of the key trench at least to 1 foot above high-flood level, should be at least 5 feet thick, and should be carried up with the embankment.

(*g*) *Berms.*—These have been noticed in (*c*) above. Their advantages are that they—

(i) Cover the hydraulic gradient of the internal percolation line (Art. 78 (*a*)), and thus render the embankment less liable to slip;

(ii) Provide space for a roadway which is better located there than on the top of the embankment;

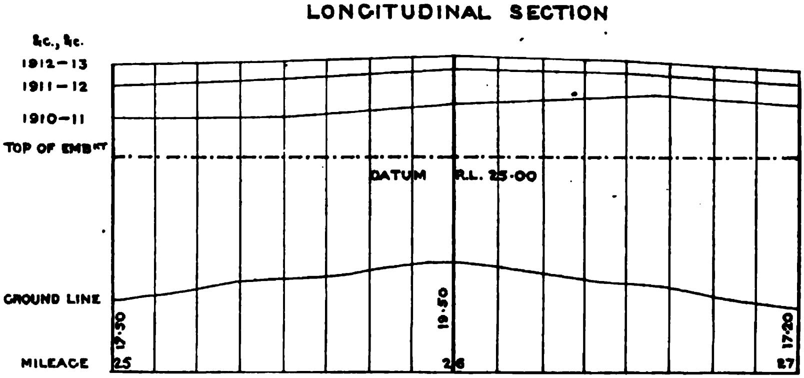
(iii) Provide space for stacking material, or an area from which soil may readily be obtained for the emergent raising of the embankment when necessary during floods;

(iv) Furnish a better cross-section for subsequent enlargement or raising of the embankment.

In America berms were sometimes placed on the river slope, but are now always formed on the land slope in order to secure the advantages enumerated above.

(*h*) *River Embankment Register.*—It is desirable to maintain a register of the embankment (furlong by furlong) in some such form as that given below, so that a proper record of the work done on it may be preserved. The record on each sheet should extend for five or ten years.

Year.	Top-Width in Feet.	Top R.L. (Average).	Free-board above H.F.L. of (Year).	River Slope to 1.	Land Slope to 1.	Length dealt with in Furlongs.	Expenditure.		Top-Width in Feet.	Top R.L. (Average).	Free-board above H.F.L. of (Year).	River Slope to 1.	Land Slope to 1.	Length dealt with in Furlongs.	Expenditure.	
							Ordinary Repairs.	Special Repairs.							Ordinary Repairs.	Special Repairs.
1910–11	6	25·4	2·4	3	2	2	Rs. 500	Rs. —	6	25·6	2·6	3	2	8	Rs. 500	Rs. —
1911–12	8	25·8	2·8	3	2	8	—	2000	8	25·8	2·8	3	2	8	—	1000
1912–13	8	26·0	3·0	3	2	7	—	1000	8	26·0	3·0	3	2	8	—	1000
etc.																



Convenient scales for the longitudinal section are:—Horizontal, 1 mile to 2 inches. Vertical, above datum, 2 feet to 1 inch; below datum, 10 feet to 1 inch.

196. Construction of Embankments.

(*a*) *General Remarks.*—Slips and leakages take place as a rule only at considerable intervals, and their occurrence is due either to bad foundations, material, or construction, or to a combination of these defects. The intervening lengths which are sound are evidence that by taking proper precautions such failures can generally be avoided. Compared with storage dams, river embankments have a large section for their height, and as a rule have to withstand only low pressures, but also have generally to be made with inferior soil. The specification for the construction of river embankments may therefore be less rigid than one for storage dams, but naturally the more carefully the work is done, the safer is it. Notes on certain matters which should receive attention are given below.

(*b*) *Material.*—The soil which exists close at hand has to be used, or the expense of construction will be greatly increased. Where, however, the surface soil is better than the subsoil, it will be better to utilise it as much as possible, and therefore within reasonable limits to increase the width of the borrow pits rather than their depth, and pay for the consequent longer lead. The best soil should be reserved for surfacing the embankment and for its upstream toe.

Lengths of the embankment adjacent to each other should not be constructed at their junction of entirely different soils, as then they will not properly unite with each other, and may settle independently of each other, which is likely to cause the formation of a leakage plane. The way to obviate this is to form between the two dissimilar soils a length of embankment as a mixture of the two gradually changing from one to the other. Such a length might be four times the depth of the plane concerned below the completed top of the bank, and with a minimum of 10 feet.

Borrow pits should never be excavated on the land side, as there they virtually increase the infiltering head on the embankment by the amount of their depth, and tend to cause the work to leak ; nor should they be continuous, as then they might lead to the formation of scour channels. They should be set out regularly so as to give the maximum amount of material from the area under excavation.

Boundary trenches can conveniently be excavated during the construction of the embankment, and the spoil from them utilised for raising it. They may have a bottom-width of 4 feet, a depth of 5 feet, side slopes of 1 to 1 next the bank and ½ to 1 away from it, and the top edge of the latter may be 5 feet inside the boundary on which itself a live hedge can be planted. At every furlong a blank space 10 feet wide should be left to prevent a scour channel forming, and this should be carefully hedged across. Such trenches effectually stop cattle trespass, and cost but little to maintain, as the spoil from re-dressing them when necessary can be utilised on the maintenance of the embankment. They are much superior to and more permanent than dry thorn hedges, which do not last more than two years when subject to immersion, and are difficult to maintain.

(*c*) *Layers.*—The earthwork should be carried up in layers, which should be level in cross-section and also in longitudinal section for the greatest length practicable. It is in respect to the latter that mistakes are often made, as the work is frequently constructed up and down longitudinally owing to the labourers not being distributed so as to secure uniform vertical progress. An irregularly-formed embankment cannot be properly consolidated, and each step in its longitudinal section is apt to form a leakage plane. To prevent this, each layer should be ended off irregularly in plan. Before fresh earthwork is placed in continuation of its end, that should have loose earth removed and be roughened by joggles and tongues (Fig. 28, p. 188) so as to break the line of junction. The advantages of constructing an embankment in long level layers are:

(i) Fewer junctions (and thereby possible leakage planes) will be formed;
(ii) Much heavier rollers can be worked, and greater consolidation can be obtained;
(iii) Rolling will be cheaper, as the rollers will have to turn less frequently.

The thickness of the layers should be at a minimum near the base, so as to secure the maximum consolidation there, where the pressure of infiltering water is the greatest. In ordinary embankments of height not exceeding 15 feet the bottom layers should roll down to not more than 5 inches, and the upper ones may be increased gradually to 8 inches.

(*d*) *Consolidation.*—The leading fact to be remembered in regard to earthwork to be subjected to water pressure is that it does not form a rigid construction, and therefore must settle. Everything should accordingly be arranged with a view to securing that the settlement shall occur only to a small extent, regularly and slowly. If it takes place excessively, irregularly, or quickly, leakage planes may result, and these, when once formed, are likely not to heal of themselves, but to remain as places of weakness, which may cause failures even after many years. It may be taken as an axiom that a repaired embankment is never so sound as one that was originally well constructed and has not failed.

In Sind the most satisfactory embankment has been found to be one made of sand, as that material is insoluble in water, is not affected by deliquescent salts, is exactly of the same character throughout, and although it settles quickly when wetted, always sinks uniformly and never has a leakage plane, as its particles continuously remain in close contact with each other; its one disadvantage is that water may percolate through it so as to sodden the ground under and near the bank. It is desirable that other materials of which embankments are to be formed should be treated as far as is practicable so as to resemble sand in the above-mentioned favourable characteristics, and surpass it in water-tightness. In the case of storage dams the attainment of compactness is facilitated by wetting the soils, but wetting is generally not practicable for the embankments of alluvial rivers, as water is usually not available. Moreover, the soils procurable for them are less clayey and compressible, and more permeable than those utilised for the first-named works. For these embankments reliance must therefore be placed on consolidation in the dry, whereby all the particles of earth are crushed into intimate and regular contact with each other, so as in this respect to resemble sand. Earth when dry is in its densest condition, and therefore, if an embankment is made of it, and all of its particles are in close contact with each other, and not separated by comparatively large interstices, such as exist between unbroken clods, then the effect of the wetting of the embankment by the river will be to make those particles swell and the whole mass still more compact and free from leakage planes. Uncrushed clods retain their individuality even when wetted, and when they dry again will more or less resume their former condition of separation from each other, so that an embankment formed of them will for years be liable to fail on account of leakage passing between them. Ramming (even when conscientiously carried out, which is seldom) is quite incapable of crushing the clods completely—that can be done effectively only by rollers. The best type of roller has a diameter of 2½ feet, and a length of 4 feet; it is split in the centre to facilitate turning, and weighs 21 cwts. empty and

33 cwts. full. An empty roller should be run over the layer until all clods are flattened, and then it should be completely consolidated by passing over it a filled roller.

The allowance for the settlement of a large storage dam is only one-thirtieth to one-thirty-sixth of its height, whereas that for an unconsolidated river embankment is usually one-tenth of its height. So much settlement involves the danger of failure when it occurs quickly, as it may do, owing to the rapid rise of the river against new bone-dry earthwork. Proper consolidation will ensure that settlement takes place slowly and uniformly, and will reduce the amount thereof to about one-fourth, and the liability to failure in greater proportion. It will also steepen the gradient of the saturation line (Fig. 95, p. 392) by making the embankment more water-tight. This shows how important it is to effect it. Even when an embankment has been thoroughly consolidated artificially, it will still settle further by its own weight, so that the longer it can be allowed to do this before it is tested by the river the better.

(*e*) *Supervision.*—River embankments have usually to be made very quickly, and are of considerable length. To ensure sound construction it is necessary that labour on it should be concentrated on a continuous length at the same time so that it may be closely supervised. The best supervisors available should be placed in charge to prevent bad work being done, as that can easily be hidden and cannot be detected until the water comes against the embankment, when its existence is likely soon to be proved by leakages, slips, and perhaps breaches occurring.

197. Wetting Embankments.

(*a*) *General Remarks.*—As river embankments have to be made of bone-dry earth, there is always danger of an accident happening should the river rise quickly against a new bank. This danger is due to the rapid and considerable settlement of the earthwork when newly wetted, and can be much lessened by properly consolidating the bank as just described. For an ordinary bank the precaution taken is to admit the river water slowly by means of sluices in the front embankment which is under replacement by the new loop. The maximum rate of rise of the water should be restricted to 3 inches a day, and should be regulated by observations of small gauges erected for the purpose. Several proposals and experiments for wetting embankments have recently been made in Sind, and descriptions of the former are given below.

(*b*) *The Wetting Channel System.*—As the area between the river and the embankment may be very large, it may take a long time to flood it. Unfortunately, as the river bank is usually higher than the base of the embankment, when the former is well topped by floods, the rise against the latter will be sudden and considerable. To obviate this danger it has been proposed to construct small front embankments, say, 500 feet upstream of the main one, and to fill with water the enclosed area by channels cut from the river. Or, as a cheaper arrangement, a good-sized channel could be cut all along the upstream face of the embankment in order to wet it. This would supply all watercourses passed *en route*, and would be led in inverted siphons under main canals.

(*c*) *The Compartment System.*—This system consists of a double line of parallel embankments connected at intervals by cross banks which form compartments whereby damage can be localised should a breach occur anywhere. The sections proposed are:

Embankment.	Top-Width, Feet.	Free board, Feet.	Slopes.	
			Upstream.	Downstream.
(1) Front or river side	6	2	4 to 1	2 to 1
(2) Main or land side	8	5	2 to 1	2 to 1
(3) Cross-banks	8	2	1 to 1	1 to 1

The centre lines of (1) and (2) were to be 250 feet, and those of (3) about 4,000 feet apart. A series of inlet and outlet sluices is proposed by means of which any compartment can be filled or emptied, and it is claimed that the area between the parallel embankments can thereby be silted up.

The advantages of the system are stated to be:

(i) Economy, as pumping is unnecessary;
(ii) Security, due to the double line of defence;
(iii) The complete wetting of the earthwork;
(iv) The silting up of the area between the parallel embankments;

(v) The testing of the earthwork higher than river H.F.L.;

(vi) The ease and safety secured for dealing with leaks and breaches.

The disadvantages attending it apparently are:

(vii) Some of the side slopes are too steep;

(viii) The expense of sufficiently strong embankments will be nearly double that of the ordinary single one;

(ix) To ensure proper silting, larger and more expensive sluice arrangements than those proposed are necessary;

(x) The crossing of canals and watercourses by the silting arrangements will be expensive;

(xi) The embankments, being independent, do not support each other;

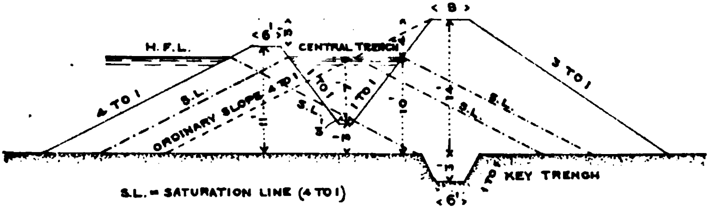
(xii) The double length of the embankments will practically double the ordinary cost of maintenance.

(*d*) *The Central Trench System.*—The cross-section of this is shown in Fig. 94. The central trench is intended to be filled at least 4 feet deep by pumping water into it well in advance of the rise of the river. The great advantage claimed for the system is that by means of it a dry embankment can be severely tested for leakages, as well as thoroughly wetted, and all leaks can be repaired before floods come against the work. The system was tried on several miles of an important new embankment in Sind. It was there found that a depth of 3 feet in the trench was ample; that the saturation line

FIG. 94

CENTRAL TRENCH SYSTEM

HOR^L TO VERT^L—1 TO 2



rose in the unconsolidated earth by capillarity to as much as 2½ feet above the water level in the trench, and its hydraulic gradient was very flat; and that the rate of absorption by the embankment rapidly decreased after a few days' flooding. The objections to this form of wetting are:

(i) The wetting first takes place high up in the heart of the composite embankment, and in the riverside portion it is in the reverse direction to that due to the river, which commences at the base of the upstream toe and rises therefrom.

(ii) The wetting constitutes an over-test of the earthwork and causes a very largely increased number of leaks and cracks to form beyond those usually met with. These may never heal thoroughly, and thus are likely to weaken the bank permanently.

(iii) The inside slopes of the trench are very much steeper than those considered necessary for the main embankment, although the saturation conditions to be met by each are similar. The result was that numerous slips occurred.

(iv) The river side embankment, being wholly separated from the land side one, does not support it; the former being virtually taken out of the section of the latter, weakens it. A single embankment is much more reliable than two small ones with a combined section not much greater than its own area.

(v) The capital cost of the wetting installation (pumping engines, etc.) was very great, and amounted to about 12½ per cent. of that of the embankment; while the maintenance cost was about 50 per cent. in excess of the usual charge.

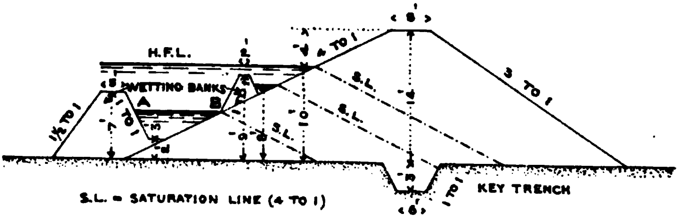
(vi) The out-of-the-way situation of the river embankment made difficult the erection of the pumping stations and their working.

(*e*) *The River Slope System.*—The cross-section of this is shown in Fig. 95. At or near the upstream toe of the main embankment a parallel bank A is formed, and the space between the two is filled with water which is admitted from the river by watercourses led from upstream, and with their beds from 3 to 5 feet below the top edge of the river bank, so as to secure early wetting. The water is allowed to rise gradually so that the embankment may be saturated in precisely the same way as the river will wet it, i.e. from the base of the toe upwards; but the artificial wetting will be well in advance of the river floods, and will be regulated, being under control. It is an engineering maxim that a good water-tight foundation is essential to the permanence of an ordinary hydraulic work.

FIG. 95

RIVER SLOPE SYSTEM

HOR^{L} TO VERT^{L} — 1 TO 2



After the base of the main embankment has thus been saturated by flow, water will be raised cheaply (by Persian wheels, etc.) to fill the wetting trench formed by an upper parallel bank, B, and sufficient time will be given to wet the embankment. If necessary, a third higher parallel bank can be formed to complete the wetting up to high-flood level, but this will seldom be required.

The small parallel banks should be connected at intervals by very short cross-banks to the main embankment, so as to form wetting compartments, which could be made to communicate with each other by pipes laid through the cross-banks and closed when necessary by sand-bags. The advantages claimed for this system are:

(i) It can easily be applied to any existing embankment without any alteration of its own structure.

(ii) It can be applied to a new embankment without in any way lessening its strength by a reduction of its slopes.

(iii) The wetting banks are quite independent of the main embankment, and their failure cannot affect it.

(iv) The wetting banks will protect the main embankment from wave-wash, so that the slope of the latter could be reduced.

(v) The extra capital cost is small.

(vi) The extra cost of maintenance will practically be nothing, as the wetting banks can be repaired by the regular inundation establishment.

(vii) The watering charges (capital and maintenance) will be small, as ordinary local appliances will be used.

(viii) The preliminary saturation of the embankment will proceed in the same way as the final one from the river, and will precede it in ample time to permit of settlement repairs. It will commence from the base and continue gradually upwards so as to allow self-consolidation to progress uninterruptedly, and so as to avoid the formation of leaks.

(ix) The compartment system can be easily applied and the number of compartments increased at little extra cost.

(x) All construction and repairs can be done locally, and expensive labour, materials, and plant are not required.

(xi) The system can be applied without any loss of time.

(xii) The system can be expanded as considered desirable so as to wet a longer length or greater height of the main embankment.

(*f*) *Reports of the Wetting of Embankments.*—As embankments in the tropics dry during the interval between two inundations, all liable to be extensively flooded by the river should annually be thoroughly wetted artificially before it rises against them. Reports on the progress made and the effects of river floods should be sent immediately after the first principal rise and at the close of the high inundation. They should state in tabular form—

(i) The approximate length (in miles and furlongs) of each continuous section of embankment wetted.

(ii) The approximate maximum depth (in feet) of the water which has risen against each.

(iii) The approximate reading of the principal reference river gauge at which the wetting of each embankment began.

(iv) Whether the embankments have stood the wetting well; whether that has caused slips or leaks, and if such accidents have been of small or large magnitude; also, how these have been dealt with and what loss of revenue and cost of repairs have resulted therefrom.

(v) What portions remain still to be wetted and what measures have been, or are proposed to be, taken to ensure their early wetting. (This item is naturally required only in the first report.)

In regard to (iv), full reports of individual bad breaches have, of course, to be made immediately they occur.

198. Maintenance and Repairs.

Maintenance is performed throughout the year by a small permanent petty establishment, and during the inundation season by a much larger special establishment; ordinary fair-weather repairs are carried out usually by petty contractors, who engage gangs of labourers.

(*a*) *Petty Establishment.*—The men have primarily to watch the embankment line and prevent trespass. They should also do petty repairs, such as making up hollows and rain scores, rooting out rank vegetation on the slopes and for 5 feet from the toes, filling rat-holes, repairing fences, repairing erosion line pegs, looking after plantations, etc.

(*b*) *Inundation Establishment.*—The first duty of the men is to watch the embankment, and when the river rises against it this watch has to continue day and night. All leaks, cracks, settlements, and breaches have at once to be made good. When the river does not endanger the embankment, petty works as above mentioned and general improvements should be attended to, so that value may be obtained for the cost of the establishment.

(*c*) *Repairs.*—These consist in keeping the embankment up to proper section and in increasing that when necessary (the latter is technically called an " extension and improvement "). As borrow pits are usually dug anyhow, advantage should be taken when repairs are extensive to set out large rectangular borrow pits, including the old ones (the contents of which should first be measured up), and to excavate the new ones regularly so as properly to utilise the excavation area. Earth washed down from the slopes should not be used for repairs, as when allowed to remain it tends to form watertight berms. Road crossings should be made up 12 feet wide, and with longitudinal ramp slopes up and down the embankment of not less than 1 in 6 for cattle and 1 in 10 for cart traffic. Platforms for establishment shelters should be made up, mileage posts painted, inspection houses and embankment sluices kept in thorough repair.

(*d*) *Establishment Shelters.*—These should consist of houses and offices for the superior staff at intervals of about 12 miles, large huts for the works staff about 6 miles apart, and small shelters for the gang men at intervals of a mile for the less important lengths of the embankment and at shorter ones at dangerous places. All these should be built just off the embankment, earthen platforms around them projecting therefrom at crest level.

(*e*) *Telephone Line.*—Important embankments have telephone lines run along them so that reports of the state of the works may be furnished daily or more frequently, and so that calls for work gangs can be made when danger threatens any point.

(*f*) *Protection from Wave-Wash.*—Where the embankment runs through an arid, sun-baked tract, grass will not grow on it, and its bare friable surface when unprotected suffers greatly from wave-wash. To protect it, reed or coarse grass mats are pegged on the slope, or rough fascines made, but these have a very short life. A more durable, but more expensive, protection is made by erecting a vertical framework of thin poles in double lines, the space between being filled with brushwood. The floating rope described in Article 183 (*b*) is not usually adopted on ordinary embankments. Brick pitching has been laid on an important embankment in Sind, and has proved successful, but was very expensive. The most efficient cheap protection is given by live growth. Tamarisk (*Tamarix Gallica*) grows profusely on riverain areas, but is so flexible that it does not give great protection unless it is in a thick belt. The best plant in Sind is the "jar" (*Salvadora oleoidas*), which has matted roots and is stiff-branched, and thus effectually deadens wave-wash; failing it, " khabbar " (*S. Persica*) is useful. The hedging should not be allowed to grow within 5 feet from the upstream toe. On high banks, in the case of tamarisk, it may be necessary to plant a line of it halfway up the bank, but if this is done, care should be taken to trim off all ground branches so that the slope may be inspected and rat-holes dealt with.

(*g*) *Embankment Extensions and Repairs*—(i) *Raising Embankment.*—When an embankment has to be raised the fresh earthwork should be added on the upstream or river side, where it will be pressed on to the old bank by the water pressure. If the addition is made on the downstream or land side, percolation water will tend to cause it to slip off. The old slope should first be carefully benched to receive the new earthwork, and that should be placed on it in thin layers sloping down towards it, and these should be well consolidated.

(ii) *Leakages.*—Leaks should be stopped from the upstream side by cutting off the penetrating water at its source. If practicable, cracks should have good earth worked into them by chisel-pointed poles, but if the presence of water against the bank prevents this, the leakage should be stopped by a cover of good earth thrown over it. Subsequently in the dry season the defective part should be cut out and properly re-made. Leakages have been stopped by throwing in sawdust, bran, etc., just upstream of them; this is carried by the water into the leaks, and becoming swollen, stops them.

(iii) *Slips and Drainage.*—Slips are due to percolation water. The fallen earth should, as soon as practicable, be cut out and then properly re-made, and the downstream toe well drained. Wherever percolation is feared, especial care should be taken to use the most impervious earth procurable in the neighbourhood for the upstream part of the section, to have a good key trench, to form the downstream portion of porous soil, and to excavate rear drains.

(iv) *Breaches.*—Whenever possible a coffer-dam of branches, brushwood, matting, bags filled with earth, etc., should be formed with its ends abutting well outside those of the breach. The coarser materials should first be deposited to check the rush of water, and the finer ones placed upstream of them. After the coffer-dam has been made fairly staunch, the bank should be restored, and to an extra large section and greater height to allow for settlement. Where a coffer-dam is impracticable, every attempt should be made by using similar materials to prevent the breach widening by holding the severed ends of the embankment.

(*h*) *Maintenance Programme for the Year.*—A programme should be made of the maintenance work to be done on embankments and canals during the interval between two inundations, so that work may be carried out promptly and systematically. It might take some such form as that noted below:

Advertisements for tenders to be sent by (close of high inundation) ....
Statement of distribution of funds by ....
Estimates for new embankments, extensions, and improvements by ....
Estimates for ordinary repairs of embankments by ....
Estimates for canal clearance, in batches from ....
,, ,, ,, last batch by ....
Canal clearance to be completed by ....
Embankment repairs to be completed by ....
Measurements to be taken during (month) ....
Check measurements to be taken during (month) ....
Canals to be ready for opening (fifteen days before inundation is expected) ....

199. Erosion Lines.

(*a*) *General Remarks.*—Immediately after the inundation the river in front of the embankment line should be inspected with a view to seeing where rapid erosion has taken place and is likely to continue, and thus to threaten the embankment. Erosion lines should be set out along the length under attack, and a plan made showing them and the river from half a mile upstream of the first line to half a mile downstream of the last line. On this plan should be marked in distinctive colours as many years' courses of the river as the record permits.

(*b*) *Erosion Lines.*—New lines should be set out at right angles to the embankment so as to register the normal width of uneroded riverain land. If the alignment of the embankment is tortuous, its average direction should be taken as the base from which the lines should be marked. If there are existing erosion lines, they should be maintained, and if they are not at right angles to the embankment, a note should be entered in the erosion statement of their obliquity and the approximate ratio of the normal to the actual oblique length of the ordinate. Where there is a distinct angle in the embankment line, two erosion lines will be necessary at the angle, each respectively normal to the portion concerned of the embankment, and, if required, a third one midway between the others. The spacing apart of the erosion lines might be thus arranged: where the river is 1 mile or less away, at every furlong; where it is between 1 and 2 miles off, at every half-mile; where it is from 2 to 3 miles distant, at every mile; where its distance is more than 3 miles, erosion lines are not wanted.

The erosion lines should be straight cleared tracks 10 feet wide, so that they can be viewed from end to end, and should start from the furlong, etc., marks of the embankment.

(*c*) *Erosion Pegs.*—(i) The pegs should be good straight pieces of rough wood about 4 inches in diameter, firmly embedded about 2 feet into the ground, and with their tops about 4 feet above it, so that they can be read when there is not more than 3 feet of water standing against them. They should be fixed vertically and in a straight line.

(ii) The chainage of the erosion line should start from the riverside toe of the embankment, and should proceed towards the river. For the length which is not likely to be eroded, the pegs should be fixed at every 500 feet. For that which may be eroded, they should be at every 100 feet, and every fifth one should be painted white to distinguish it from a distance.

(iii) Near the top of each peg and facing the embankment a place should be neatly dressed smooth between two horizontal saw-cuts. This should be painted white, and on it should be figured in black the distance of the peg in chains of 100 feet from the starting point of the erosion line. The figures to be not less than 2½ inches high.

(iv) At this starting point a peg should be fixed. It should have marked on it as a fraction 0, as numerator, denoting it is the starting point, and as denominator the total length of the erosion line at the end of the previous inundation; this latter will have to be changed yearly when the river recedes or advances.

(*d*) *Erosion Statement.*—Every week as long as erosion continues a tabular statement recording it should be submitted. The columns in this might be as follows:

1. Mileage of ordinate.
2. Date of first measurement.
3–5. Measured length of ordinate—original, last week, this week.
6–8. Amount of erosion—to end of last week, during the week, to end of this week.
9, 10. Distance remaining uneroded—along the ordinate, approximately normal to the embankment.
11. Minimum height of free-board during the week.
12. Remarks (e.g. pegs partially or wholly submerged, back loop under construction, or constructed, etc., etc.).

To save clerical labour the figures in columns 1, 2, and 3 could be printed and entries made in columns 4–10 only when erosion has taken place during the week.

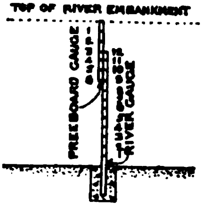
200. River and Embankment Gauges.

(*a*) *River Gauges.*—At every mile along the embankment should be a stout gauge post with an enamelled gauge plate (or with graduations cut on the post itself) facing the embankment, so that river-flood levels may be observed. The gauge post may be, say, 6 inches square in section. It should be fixed firmly in the ground, preferably in concrete, and its top should be about 2 feet above the highest known flood level. A cut should be made on it to indicate the zero of the gauge plate, and the level of that should be cut or painted on the post and carefully recorded. The gauge should be considered a permanent fixture, and as a rule should not be moved when the embankment is raised. The flood levels should be taken weekly, or daily during a high inundation, and reported. From these the gradient of the river can be determined, unless that is so far off that the gauge does not properly register it. In that event a subsidiary gauge nearer the river bank should be established opposite to the main one. The high-flood readings should be taken by a superior member of the staff to ensure correctness, as on them depends the proper amount to which the raising of the embankment, if necessary, should be designed.

(*b*) *Free-Board Gauges.*—The river gauges do not indicate directly the amount of free-board of the embankment which it is desirable to ascertain at once during inspection; more especially is this the case when the embankment has been raised subsequently to the fixing of the river gauge. To enable the free-board to be seen at a glance, a subsidiary gauge post should be fixed by cleats to the river gauge as shown in Fig. 96. This post may be 4 inches wide, facing the embankment, and 3 inches deep. It should have an enamelled gauge fixed to, or scale cut into it, reading downwards, and on the face opposite to the embankment. The colouring of this gauge should be different from that of the river gauge, so as to avoid any chance of mistakes in reading. The top of the minor gauge should be exactly level with that of the embankment, and should be altered to correspond with it when the earthwork is raised.

FIG. 96

FREEBOARD GAUGE



201. Embankment Sluices.

(*a*) *General Remarks.*—The embankment line crosses the canals and watercourses which are led from the river to irrigate the protected area. At the crossings head regulators (Art. 219) are built for the former, and embankment sluices for the latter. Each such work, unless properly constructed under the most careful supervision, would be a source of danger, as it might induce a breach of the embankment. The number of the sluices should therefore be reduced to the minimum, and wherever practicable two or more watercourses should be supplied from a single sluice, and should bifurcate downstream of it. The site of the sluice should be where the ground is firmest, say, within 100 yards of the crossing of an existing watercourse. If a new watercourse is proposed, it should be aligned so as to gain this security for the sluice.

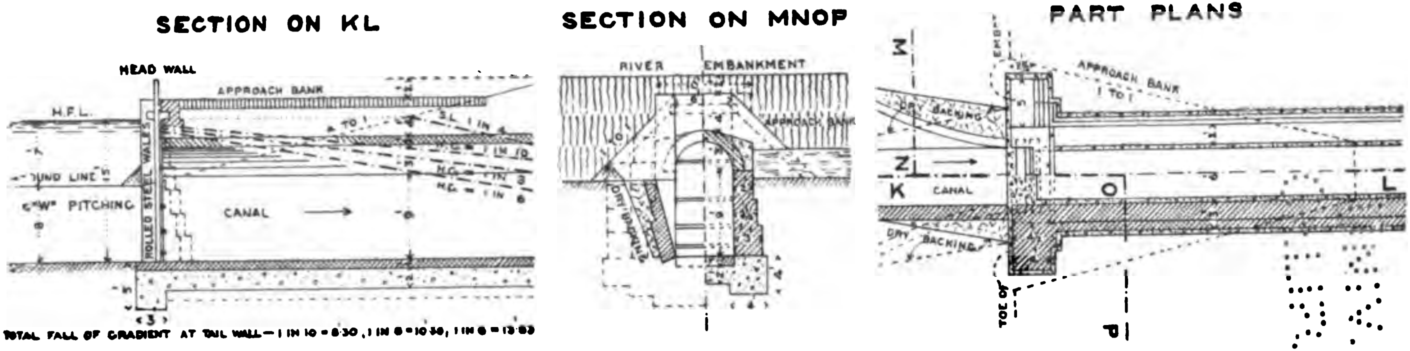
On the drawing of the sluice should be a note giving the following information:

Irrigated area served	acres.
Duty allowed	acres per cusec.
Mean velocity of channel	feet per second.
Full-supply vent area required	sq. ft.
Full-supply vent area (net) designed..	sq. ft.

FIG. 97

RIVER EMBANKMENT SLUICE

ALTERNATIVE INLET



SECTION ON KL

SECTION ON MNOP

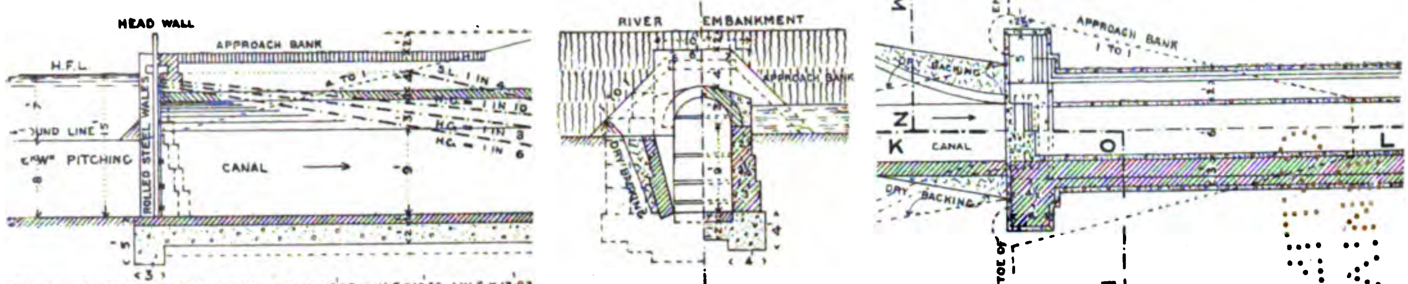
PART PLANS

TOTAL FALL OF GRADIENT AT TAIL WALL — 1 IN 10 = 8·30, 1 IN 8 = 10·38, 1 IN 6 = 13·83

FIG. 97

RIVER EMBANKMENT SLUICE

ALTERNATIVE INLET



SECTION ON KL

SECTION ON MNOP

PART PLANS

TOTAL FALL OF GRADIENT AT TAIL WALL—1 IN 10 = 6'30, 1 IN 8 = 10'38, 1 IN 6 = 13'83

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In Fig. 97 are drawings of an embankment sluice on good soil foundations so as to meet the conditions of high uncontrolled water pressure by the river and the paramount necessity for avoiding a breach. (A branch regulator, taking off from a main canal, where the water pressure is much smaller, and where in case of an accident the water can be shut off, would naturally be of less massive proportions.) The limit of the span should not exceed 10 feet, and preferably should be 8 feet.

(*b*) *Hydraulic Gradients.* (See also Art. 209 (*c*)).—In Fig. 97 two kinds of water gradients are shown. The 1 in 4 line is that of the saturation of the embankment (Art. 78 (*a*)); this is taken liberally on account of the nature of the porous soils, which are generally the only ones available for construction. The 1 in 10, 1 in 8, and 1 in 6 lines are the subsoil hydraulic gradients, which indicate for different soils the upward pressure on the foundations from point to point. They also show the lengths to which the floors of the works constructed on them must be continued, so as to reduce the velocity of subsoil flow below that which would carry away the particles of the subsoil. For this purpose the floor need not, however, be extended to where the gradient meets the bed, as it can safely be terminated where the pressure is low—the flatter the gradient, the finer are the subsoil particles, and the less should the tail pressure be. Moreover, during high floods there will always be tail water in the canal which will reduce the upward pressure.

The 1 in 10 gradient is that adopted in Sind for the worst condition, a pure sand formation. For fairly water-tight foundations the gradient might be taken as 1 in 6, and for medium ones, more or less sandy, 1 in 8; these are all liberal when compared with the line of embankment saturation. The 1 in 6 gradient is assumed in the design of Fig. 97; for flatter gradients involving higher upward pressures, the thickness and length of the foundation pavement would have to be increased to suit the conditions. The lines of the three gradients are shown also to indicate how the pressures corresponding to them vary. They start from the upstream limit of the impermeable foundations, and therefore it is desirable that that limit should be advanced upstream as much as possible.

Two alternative treatments are shown in Fig. 97—the first with, and the second without, upstream wing walls from the headwall, which in the latter case is advanced to the toe of the embankment. In both cases there are only short return walls upstream to support the approach embankment (they thus do not tend to admit water into the hearting) and none downstream (so that drainage out of the hearting is not retarded). Fig. 97 shows that the second design lowers the hydraulic gradient by an amount corresponding to the drop in level due to a length of 18 feet. This is effected at the comparatively small extra cost involved by the substitution upstream of that length of closed culvert for the similar length of open channel between the wings in the first design.

(c) *Curtain Walls.*—It is held by some that the effect of curtain walls is to add twice their depth projecting below the ordinary foundation to the length which the subsoil water has to traverse; the hydraulic gradients have been drawn accordingly in the figure. That view assumes that this water will descend down the upstream face of the curtain and ascend up its downstream face. Water, however, follows the easiest course, so that its actual path will depend upon the relative water-tightness of the subsoil at different levels. If that increases regularly from the surface downwards, the percolation water will tend to rise to the top, and thus its course will be as anticipated by the above-mentioned view. If, however, the subsoil at or below the foundation is more porous than it is at the surface, the water will percolate through the lower layer and the presence of curtain walls above that will not increase the length of its travel.

Others consider that the utility of curtain walls lies in their cutting off direct leakage planes in the subsoil as far as they penetrate it; also in reducing the extent of the subsoil area through which percolation takes place. This seems the more correct opinion of the two. Anyhow, whichever is the right idea, it appears desirable to make curtain walls of some depth. To be effective they should project at least 3 feet below the beds of the pavements against which they abut. Where, however, subsoil water is met with at a higher level the depth may have to be reduced. Where the soil is friable, the excavation for the curtain wall is likely to disturb it (which is against having a deep wall there), and the refilling of the foundation trench must therefore be most carefully done.

(d) *Downstream Pitching.*—A rule in Sind to determine the length of this is that it should extend to a point distant from the upstream face of the sluice ten times the head on that face diminished by 3, i.e. to (Head—3) × 10 feet. Another rule is that the length of the downstream pitching should be ten times the ordinate of the hydraulic gradient at the down-end of the masonry pavement of the culvert. These lengths seem to err on the side of safety, and are in excess of what has been constructed at many existing sluices. With a properly designed culvert the hydraulic ordinate at its downstream end will be small, and there will not be much blowing up effect there. What has chiefly to be considered is the scouring action of the water issuing through the sluiceway. To meet this in the Figure a water cushion with gently inclined bed slopes is shown.

(*e*) *Length of the Culvert.*—In the old pattern of Sind sluice the abutment was very short, and the return walls carried the parapet as in the case of an ordinary bridge (see Fig. 14, p. 73). Thus the river water was admitted on the upstream side along the return walls to near the centre of the embankment, the resistance of which to percolation was thus considerably reduced. Fig. 97 shows a much greater length of abutment, and very short return walls at the upstream toe only, and remote from the centre of the embankment, and is thus a great improvement. If it is necessary to lengthen the pavement of a sluice in natural ground so as to increase the resistance to creep along it, it would appear proper similarly to lengthen the superstructure, which is in made ground.

(*f*) *The Staunching Wall.*—This wall is a most important part of the design in regard to the prevention of leakage past the work which might lead to a breach. The lower view of Fig. 14 (p. 73) illustrates the plan of a breach which occurred at a sluice of the old pattern with long return walls admitting water near the centre line of the embankment. In that design the staunching wall was made of less projection into the bank than the return walls; consequently it did not cut off percolation passing beyond them, and thus had no effect in preventing a breach. The difference between a staunching wall projecting horizontally into a made embankment and a curtain wall descending vertically into natural ground is that the former, as its length is increased, does not penetrate into denser earth, as generally does the latter, and hence is not so effective in stopping creep. The projection of the staunching wall beyond the ends of the return wall should therefore be of some length. To lessen the cost the return walls should be as short as possible. While an upstream return wall has a tendency to admit water into the heart of the embankment, a downstream one has a tendency to imprison the water in the bank. Both return walls thus diminish the effect of the staunching wall. It will be seen from Fig. 97 that the upstream one is there very short, and is placed at the toe of the embankment, while the downstream one is omitted.

The staunching wall should be raised at least to the 1 in 4 saturation line, where that is crossed, but it will be better to raise it still higher. The junction of masonry and earthwork is a place of weakness: at it there is a tendency for a leakage plane to form, especially when the latter is green and capillarity takes place; should that plane develop it will probably extend to the top of the bank, and water will pass along it with little loss of head. It seems therefore advisable to raise the top of the staunching wall to river high-flood level, more especially as that level may be increased (Art. 176). This wall should be bonded water-tight with the rest of the superstructure, and its foundations should be carried a little below those of the culvert pavement.

To prevent the earthwork during settlement from resting on the top of the staunching wall that should be rounded off, and to stop the earthwork from parting from the wall, the sides of that should be battered at 1 in 12 and its end at 1 in 4. The first batter will also increase its thickness and staunchness towards the base, where the water pressure is greatest. To stop creep along the abutments a casing of good clayey earth free from all porous material should be formed in thin layers, which should be watered and carefully rammed against the superstructure.

(g) *Inlet and Outlet Arrangements.*—The approach to and exit from the sluiceway should, as far as practicable, have a waterway similar to its own; thus when wing walls are built they should be in line with the abutment. The water will then enter and leave the work regularly. Any sudden enlargement, such as would be due to divergent wings, would cause eddying motion, and this would form a pothole close to the work and endanger its safety. With a proper inlet and outlet having parallel sides the current will leave the work in a direct line, and any pothole that may be scoured out will be formed some distance downstream, where it will do little or no harm. For this reason in Fig. 97 the side pitching is made vertical at the ends of the parallel wings, and its slope gradually increased therefrom to that of the open channel excavation. To reduce earth pressure the steep part of the pitching is backed with dry material.

(*h*) *The Pavement.*—In Sind the bottom of the sluice waterway is formed with an invert so as to resist the upward pressure of the subsoil water. This involves closing the ends of the invert by horizontal sills, the downstream one of which obstructs the flow of the water and tends to produce irregularity of flow. To avoid this a flat pavement seems better, and its thickness can be made sufficient to resist upward pressure; as the span is small, this thickness need not be great.

(*i*) *Wales and Needles.*—The area of the opening of the sluice waterway is regulated by means of movable vertical needles, which are supported against the water pressure by fixed horizontal wales. The obstruction to flow by the wales may be taken as equivalent to one-and-a-half times their own area, and this has to be deducted from the gross waterway of the sluice to give its net effective waterway. The top wale should be placed just above full-supply level, so that it will not obstruct flow. The sill of the sluice should be made of a stone or wood lintel, so that the feet of the needles may abut closely on it and not injure it. In Fig. 97 provision is made for downstream needles at the tail wall so that these can be inserted when from any cause it is necessary to control the flow of water which has entered the sluice.

(*j*) *Pitching.*—Where the head on the downstream pitching of the bed is considerable, that should be built of brickwork in mortar to resist blowing up. Where the head is less than 5 feet, the pitching should be of dry brickwork laid in cells formed of bands of brickwork in mortar, and on a layer of permeable brick ballast, etc., to let percolation water escape. The pitching of the sides of the channel should be of dry brickwork. It has been proposed that alternate courses should be made to project ¾ inch from the face to stop wave-lap.

(*k*) *Construction Details.*—(i) Only thoroughly burnt bricks, and preferably ones somewhat overburnt, should be used, as underburnt ones are attacked by salts in the earth.

(ii) Large batters should be built with specially moulded bricks to avoid the waste of cutting. For a batter of 1 in 8 the wall may be built with ordinary rectangular bricks, as the offset of each course is only $\frac{3}{8}$ inch, and this amount will not prevent the earthwork following the general slope during settlement. For such a batter and for slighter ones neither special bricks nor cutting is therefore necessary.

(iii) Excavation trenches should be taken out with a small side slope. The filling for 5 feet all round the back of the superstructure should be of the best sweet earth procurable within half a mile, and free from all porous matter. It should be formed in 3-inch layers, each of which should be thoroughly consolidated, and then have its surface slightly wetted to receive the next layer.

(iv) The rolled beam wales should be fitted in recesses for easy removal for annual painting, and should rest therein on stone sills and distance pieces.

CHAPTER XV.

SILT IN ALLUVIAL CANALS.

202. General Remarks on Silt.

(*a*) *Classifications of Silt.*—Silt is the name given to all matter, both inorganic and organic, brought down by water. Thus it includes boulders, pebbles and gravel, coarse and fine sand, clay and earth, also vegetable and animal *débris*. All silt is derived from the washing down of the catchment area ; that which is directly due to this may be called "original silt," while that which is produced by the scour of the bed and erosion of the sides of the channel may be called " local silt." In non-alluvial countries this scour and erosion may be of local soils which have disintegrated *in situ*, while in alluvial ones it will be of alluvium previously carried down and deposited.

Inorganic silt may be divided into soluble and insoluble silt ; organic silt will eventually after decomposition be chiefly soluble. Soluble silt fertilises the soil, and as much as possible of it should therefore be brought on to irrigated land, which it will greatly benefit ; when not in great excess it will be consumed by the growth of the crops, and will thus not raise the level of the fields. The poorest land can thus be rendered fertile by silting up, warping or colmatage, as the process of artificially causing the deposit of soluble silt on it is variously called. Insoluble silt, if deposited in the irrigation channels, tends to choke them and to interfere with their regime ; if carried on to the fields, it tends to render them sterile, and to raise their levels permanently. The object of the engineer should therefore be to admit as little of it as practicable into the irrigation system.

Lastly, silt may be classed as " bed silt " and " suspended silt " ; the former consists of heavy particles which are rolled along the bed of the channel in a series of gentle serrations or waves, and travel with a very small inclination to the crest, after which they drop down to form a steep slope. The latter is continually dropping down through the water, and thereafter is buoyed up by eddies, while at the same time it is carried forward by the current. Bed silt should be reduced to the minimum, as it has eventually to be removed, while suspended silt should automatically be carried on to the fields. Clayey silts have the advantage that they tend to waterproof the channel, whereas sandy silts cause it to remain porous.

(*b*) *Production of Silt—Alluvial and Non-alluvial Rivers.*—The amount of silt brought down by rivers varies greatly owing to the differences of the physical characteristics of their catchments (Art. 64 (*a*)) and to the variation of their meteorological conditions. In respect to the latter, both great heat and great cold disintegrate soils and render their surfaces removable by heavy rainfall. Generally speaking, the amount of silt brought down by alluvial rivers far exceeds that transported by non-alluvial rivers owing to the greater friability of the surfaces of the catchments of the former. Silting is also caused by variation of flow in a river or canal itself, for where the velocity is checked, the silt is deposited, and may not be removable when the ordinary velocity is restored.

In an ordinary non-alluvial river silt is not of much moment either in regard to adding fertility to irrigated lands or in causing difficulties in the irrigation channels. In an alluvial river silt is, however, a matter of the first importance, and one which demands the most careful attention of the engineer in the design and maintenance of his works. He has, in fact, to consider not so much how the action of the water but how the behaviour of the silt will affect them. Silt is said to attract silt ; this is due to the lessening of the velocity by the deposit, and indicates the necessity for preventing the formation of that. In the following paragraphs alluvial rivers will therefore be dealt with chiefly. The silting of reservoirs has been discussed in Article 64.

(*c*) *Quantity Variation of Silt.*—The amount of silt in a river varies according to the season ; it is greatest at the beginning of the flood period, when the surface of the catchment which has been disintegrated during the preceding fair weather is washed off by the first heavy falls of rain ; it is least at the end of the fair weather, as the discharge then is not only at a minimum, but is also least turbid, seeing that it derives silt solely from a little local erosion, and only clear percolation water from the catchment generally. The maximum amount of silt is usually carried by a rising river before the peak of the flood has been reached; when that occurs some of the silt has already been deposited in the channel higher up, as then the flood was there at its maximum. The silt is not evenly distributed throughout the depth of the stream, but increases considerably in amount from the surface to the bed. In a regular flowing channel the silt is probably in largest quantity near the sides, owing to retardation of flow there.

(*d*) *Grading or Analysis of Silt.*—As heavy silt grains are likely to be deposited in channels, while fine particles may be carried on, it is desirable to test the nature of the silt of the source of supply and to grade it, care being taken to obtain a truly representative sample of the sand. The analysis is made by dropping the sand into a vertical tube filled with water, and terminating in a graduated glass measure. The velocities at which the last and first grains fall are noted, and the sand is classified accordingly; thus, if the velocities are respectively 0·05 and 0·25 feet per second, the silt would be said to be $\frac{0·05}{0·25}$ grade. When the water in the river is heavily charged with silt, as little as possible of it should be admitted into the canal, and that only from the surface.

One cubic foot of damp silt contains about 50 lbs. of dry silt to 45 lbs. of water, i.e. has a total weight of about 95 lbs.

203. Kennedy's Theory of Silting.

(*a*) *General Remarks.*—The theory in accordance with which modern alluvial canals are designed in India so as neither to silt nor to scour is due to Mr. R. G. Kennedy,[1] C.I.E., who has published diagrams which enable a canal section to be readily selected of the proper bed-width and full-supply depth for any desired discharge at any ordinary bed inclination that will be non-silting and non-scouring.

According to this theory the silt-carrying capacity of a channel varies directly with some function of the mean velocity and inversely with some function of the depth of supply, hence a broad and shallow channel will usually silt less than a narrow and deep one. Although there is an increase of velocity when the ratio of depth to bed-width is increased, the larger the ratio, the greater also is the velocity required to prevent silting, so that the advantage of increased velocity is more than neutralised by the disadvantage of increased depth. Large channels of over 50 feet bed-width cannot, however, be designed in accordance with the theory, as their ratio of bed-width to depth is governed by practical considerations; it is chiefly in the design of branch canals, and especially of water-courses, that the theory is of use. Shallow, broad channels silt much less at the head than narrow, deep ones, and the silt is thereafter carried down uniformly. In their case a further advantage accrues from increasing the ratio of bed-width to depth in that the range between ordinary and extra-ordinary full-supply depth will thereby often be reduced. There will thus be a smaller range of variation in the working heads of the outlets, and particularly of the upper ones, which otherwise often draw off more than their fair share of large supplies. The theory involves the construction of wide channels, and thus increases the cost of construction owing to the longer lead entailed, and to the greater width of land to be acquired.

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[1] Minutes of Proceedings, Inst.C.E., Vol. CXIX, Paper No. 2826; Punjab Irrigation Branch Technical Paper No. 7; and "Graphic Hydraulic Diagrams," Thomason College Press, Roorkee, India.

Mr. Kennedy based his theory on many observations of the Bari Doab Canal system in the Punjab on channels which neither silted nor scoured. He found that these were characterised by a nearly rectangular cross-section, the sides being vertical and of fine sediment, and the bed horizontal and of coarse sand. While deposits occurred at the heads during the flood season, the material was picked up by the clear water of the fair season and carried forward.

(*b*) *Motion of Silt in Suspension.*—If silty water is poured into a vessel and allowed to stand, the originally suspended matter will eventually be deposited, the heavier particles rapidly and the lighter ones much more slowly. In a frictionless channel flowing with perfect regularity the particles would settle in the same times, and would thus be deposited down its course in lengths corresponding to the distances traversed by the flow during those times. A frictionless channel is an impossibility, and even were it originally possible, this character would be destroyed by the deposits on its bed and sides, which would roughen them and produce eddies such as always occur in practice. The effect of the roughness of the sides is to produce eddies which are chiefly horizontal, and thus do not much influence the onward travel of the silt particles. The roughness of the bed, however, causes vertical eddies, which bring up the particles from the bottom to the surface as gravity causes them to descend. The silt is thus kept in suspension while the velocity of the current carries it forward. Thus the transporting power of a current depends more on its cross-currents, eddies, and whorls than on its forward velocity. This action is confined to suspended silt, and does not affect the heavy bed silt, as that cannot be lifted by eddying motion, but is rolled along the bed by the forward velocity of the current. It has been stated that the power of water to hold matter in suspension is directly as the velocity and inversely as the depth. The explanation of this is apparently that the eddying motion producing suspension is itself a product of the onward velocity, and that the less vertical distance a given eddy has to travel, the more effective is it in buoying up silt.

(*c*) *Kennedy's Theory.*—This is embodied in the equation—

$$V_o = cd^m$$

where V_o is the "critical" mean velocity—non-scouring and non-silting.

c is a co-efficient taken as 0·84 in the Punjab, three-quarters of this, or 0·63, in Sind, and two-thirds, or 0·56, in Egypt; in Burma it is taken about 0·91; it decreases with the fineness of the silt.

d is the depth of the supply.

m is a factor usually taken as 0·64, but in Burma as about 0·57.

The mean velocity, V_o, must not be kept constant in all channels of a system, but must be varied with their depths in accordance with the equation. When the nature of the soil permits, a greater velocity than V_o may be given, but a smaller one never, or silting will occur. When V_o can thus be increased, so also may d be made greater; in other words, quick-flowing canals should be narrow and deep, while slow-flowing ones should be broad and shallow. In the case of a very sandy soil V_o is the only velocity which will maintain the regime of the channel.

On different systems *c* and *m* may vary, but probably only very slightly; the value of *c* apparently increases in proportion to the ratio of silt to water, while *m* increases as the silt becomes coarser; fine silt has a lower critical velocity, V_0, than heavy silt. A practical inference from this is that the depth of flow should be decreased when the water is turbid and increased as it becomes clearer; this will reduce silting to the minimum.

(*d*) *Ratio of Bed-Width to Depth.*—It will be noticed that the equation does not take into account the ratio of bed-width to depth, but the two factors are naturally interdependent, and the theory indicates that the ratio should be considerable, that is, broad, shallow channels silt less than deep, narrow ones. Kennedy's diagrams show that the former, although they have a small hydraulic mean depth, are non-silting, with flatter bed slopes than the latter, which have a large hydraulic mean depth. The reason of this is that each vertical eddy buoys up its own quota of silt, and the total silt-carrying capacity of the channel is the sum of this effect of the individual vertical eddies distributed throughout its breadth. As previously explained, eddies are most effective when their travel is short, i.e. when the channel is shallow, which for any given discharge implies that that must be broad.

It is generally considered that for channels discharging from 50 to 250 cusecs, the ratio of bed-width to depth should be about 5 to 1.

(*e*) *Effect of Application of Theory to Silt-Carrying Capacity of Channel.*—In a Kennedy channel the silt is moved on more rapidly and uniformly than it is in one which has a smaller mean velocity in proportion to its depth. Thus if the flow in the case of the former is in any way disturbed, local silting may take place more quickly than it would do in that of the latter. A Kennedy channel does not lessen the amount of silt admitted (except by preventing erosion down its course); all that it does is to keep the maximum amount of silt in suspension for the greatest length of time, thus enabling it to be passed away at outlets. It therefore tends to lessen silt deposit in the main channels, and to increase it in the watercourses and on the irrigated lands. To reduce the amount of heavy silt admitted and to deal with that which is deposited in the channel other arrangements have to be made, and these are described below.

204. Reduction of Silt before Admission.

(*a*) *Measures to be Adopted.*—Heavy silt is picked up from the river bed when the velocity is irregular and high, and is carried along in the lower strata of the current until it is deposited. To reduce its amount the following measures have to be taken accordingly to prevent its admission as far as practicable:

(i) The undersluice gates, which are close to the head regulator, to be closed as long as possible so as to reduce the velocity of approach to the canal.

(ii) The head regulator gates to be closed when the undersluices are opened to discharge floods or to scour out deposits upstream, so as not to admit disturbed silt-charged water.

(iii) A silt trap (see (*b*) below) to be formed in the approach channel upstream of the undersluices by a divide wall built at right angles to the weir. The silt deposited therein to be scoured out by opening the undersluices at intervals. The divide wall concentrates the current to the undersluices, and thus increases their scouring capacity.

(iv) The waterway of the head regulator to be increased beyond that of the canal, so as to reduce the velocity of the water at the intake.

(v) A small discharge to be admitted into the canal when the water is very turbid, and a large one when that is clear (Art. 203, end of (*c*)).

(vi) Only the clearer surface water to be admitted from the river into the canal; this can be arranged for by constructing a raised sill (see (*c*) below) across the head regulator, and by making the sluice gates lower to open, so as themselves to form a rising sill.

If heavy bed silt is once admitted, it will pass down when flushed and do harm unless it is discharged at escapes; every precaution should therefore be taken to prevent its entry into the canal. As far as possible only light suspended silt should be taken in, for which purpose analyses of the silt content of the river water should be made, and the supply regulated accordingly. Owing to heavy silting it is occasionally necessary to excavate new canal heads.

(*b*) *Weir Silt Trap* (see (*a*) (iii)) above.—The weir silt trap acts chiefly in the flood season when the heaviest sand is borne down by the river. If this is allowed to remain in front of the head regulator, some of it will subsequently be picked up and carried through that; the trap should therefore be worked as frequently as possible, and especially when the flushing head is good. In the fair season little coarse silt is brought down, and the bulk of the silt is fine and is carried into the canal despite the silt trap. Moreover, then, flushing discharges cannot easily be arranged for owing to the low state of the river, and the demands of irrigation for the whole supply. The effect of working the trap should be ascertained by soundings before and after the scouring has taken place, and by silt analyses of the water in the river and in the canal.

(*c*) *The Raised Sill* (see (*a*) (vi)) above.—An objection made to the raised sill (Art. 219 (*d*) and Figs. 116, 117) is that it tends to cause a swirl in the river bed which lifts the heavy bed silt and thus defeats the object of the sill which is to impound that. This defect might possibly be met by constructing a gently inclined pitched apron leading up to the crest of the sill.

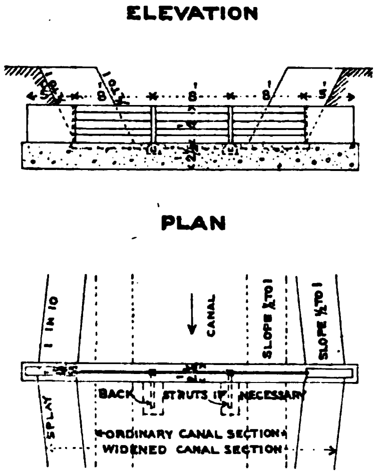
In order to deal with this heavy silt in America a trial has been made of sluices in the raised sill, through which the bed silt passes and is conducted under the canal and back to the river in curved culverts. This arrangement is expensive, and requires a large surplus supply to work it, but that should be available in the flood season when the silt is most abundant.

A better plan is in successful operation on the Sone Main Western Canal in Bengal, where a supplementary surface inlet was constructed in the river bank some distance upstream of the weir, and the channel from it was led into the main canal downstream. The floor of the inlet was made 3 feet above the level of the top of the lower shutters of the main head regulator, and baulks were placed in the vents of the inlet so that the depth of water flowing evenly over them was never more than 2 feet. Heavy silt was thus prevented from entering the inlet channel; only fine muddy silt passed down it, and the bulk of this was carried on to the fields.

(*d*) *Silt Regulators.*—The raised sill is impracticable across the head regulator of an inundation canal, which may be situated some miles away from the river, as it would cause the whole inlet channel upstream of it to silt up solid to its crest level, and would thus seal the canal when the river fell below that level. As it is, these long, open, and unprotected inlets are peculiarly liable to silt, as they ordinarily form long pools in which the current is very slow. To increase the velocity through them it is advisable to place the silt clearance spoil alongside as continuous canal banks in order to shut out the river overflow, and, near the river inlet, to form one or more cross-banks on the canal berms, so that these may be silted up and the silt-admitting flood waterway at the head may thus be reduced. The raised sill device may, however, be imitated by constructing across the inlet channel, just beyond the probable limit of erosion by the river during the following flood season, a cheap temporary "silt regulator" (Fig. 98). This might consist of a brickwork sill built across the canal bed with small grooved brickwork flanks let into the sides of the canal. The length of the sill might be divided into bays by removable vertical rolled joists let into cast-iron sockets, with their tops, say, 4 feet above sill level, and spaced from 6 to 8 feet apart. If necessary, these joists should be supported by removable angle iron struts riveted to their tops and each secured at its own base by a nut to a lewis bolt embedded in the foundation. Between the flanks and the rolled joists horizontal wooden planks would be placed. The silt regulator would be left open until the canal began to flow, say, 2 feet deep, and the planks inserted to keep pace with its rise; these would finally be removed as the river fell permanently below their tops. During the interval the planks would be left in place, and would thus prevent the entry into the canal of the heavy silt-charged bottom water. The silt which will accumulate in the comparatively short length of

FIG. 98

SILT REGULATOR



the canal upstream of the regulator will be washed down the canal when the planks are removed, and this process could be accelerated by stirring up the silt by hand. To get sufficient supply from a thin film of surface water, the canal would have to be widened at the site of the silt regulator, which would be correspondingly lengthened. An unsuccessful trial of this device was made in Sind, but the arrangement seems worthy of more extended experiment on canals where it is likely to prove successful.

205. Removal of Silt Deposited.

(*a*) *Measures and Works Adopted.*—The following measures and works have been adopted to remove silt which has been, or is likely to be, deposited in a canal:

(i) Grading, sectioning, and aligning the canal.
(ii) Flushing the canal.
(iii) Silt-scouring fleet.
(iv) Silt escapes.
(v) Silt traps.
(vi) Excavation.

Nos. (ii) to (v) are applicable only to a main canal, while (i) and (vi) can be carried out on all parts of the system. The last is most easily effected on branch canals and their subsidiaries, as they can be closed in rotation and the work executed in the dry. Generally, a main perennial canal cannot be closed long enough to allow of complete clearance, and should therefore, as far as possible, be designed to be non-silting. The clearance of a main canal is naturally more expensive on account of the increased lead and lift than that of a minor channel.

(*b*) *Grading, Sectioning, and Aligning the Canal.*—(i) Although the first deposit of fine clayey silt may improve the discharging capacity of the canal by increasing the smoothness of its wetted perimeter, further deposits are likely to be irregular, to diminish that capacity, and prejudically to affect the regime. A deposit of silt is evidence that the velocity of flow is insufficient to carry forward matter which should be kept in suspension, and, where it is sudden and irregular, that the velocity has been abruptly checked. Such excess silting occurs chiefly at the heads of the canal, and its branches and watercourses, as there the water has to change its direction, and therefore produces silt-lifting swirls, and also loses velocity. It is thus advisable to grade the head of the canal downstream of the regulator as steeply as practicable, in order to increase the velocity there up to the limit which the ground can stand without erosion. Thereafter a less inclination and a lower velocity downstream will permit of the forward transport of much of the silt (middle of Art. 36). That inclination and velocity can be determined by the use of Kennedy's diagrams, and will vary as the discharge of the canal diminishes from head to tail. Similarly, the head section of branch canals and distribution channels should be allowed increased velocity. An opinion held by many is that if the ratio of bed-width to depth of the canal is made the same as that of the river which supplies it, the former will neither silt nor scour. The ratio of silt to water should by proper arrangements be less in the canal than in the river ; as the general inclination and velocity of the former will usually be smaller than those of the latter, the two opposing factors may thus be made to counterbalance each other. Another opinion held is that to reduce silting to the minimum the velocity of the canal should be the same as that of the river ; as the latter will ordinarily be naturally the greater, it will have to be reduced, as explained in the last Article. In Egypt it has been found that with velocities from 2·3 to 3·3 feet per second silt is not deposited in the canal ; with smaller velocities heavy silt is deposited, and, finally, fine mud, when the rate of flow is decreased to 1·33 feet per second. Too high a velocity should be avoided, as it will tend to cause the canal to erode its banks.

(ii) The cross-section of the canal should be just sufficient for its discharge ; any increase of it beyond this amount, and especially any sudden enlargement at the head (where shingle may be deposited), will lead to reduction of velocity and consequent silting. Muddy silt deposit in the canal is an indication that its waterway is too large. As the velocity will be reduced when the surface level of the canal and its discharge are lessened, which will happen when the river lowers, there will then be a tendency for silt to be deposited ; fortunately, at such times the silt content of the water will be smaller, and this will act as a set-off. To prevent silt deposit owing to lessened discharge, watercourses (which are under control) should be made to flow at full supply. When a main canal silts, its waterway should be reduced; this can be effected by constructing groynes or spurs in pairs opposite to each other of a projection, and at a spacing which experiment will determine; the groynes may be of stone, timber, or even brushwood. Removing silt deposits by excavation is only a temporary remedy, for as the conditions tending to cause silting are thereby only slightly modified, fresh silt will soon take the place of that removed.

(iii) The alignment of the canal should avoid sharp curves which may cause bed scour, as that will produce local silt deposits, which will injure the regime of the canal. Bank erosion may have to be prevented by building groynes at the places attacked. Erosion and scour will also take place if the velocity is too great; when this occurs it may be necessary to reduce the bed inclination by the construction at intervals across the canal of raised bars or vertical falls. The deeper the channel, the less likely is it to scour; and the coarser the bed sand, the less is the effect of the depth. The minima velocities of clear bottom water which will just transport materials are approximately:

	Feet per Second.
Soft earth to soft clay	0·25 to 0·50
Sand, finest to coarse	0·50 to 0·80
Coarsest sand to gravel (1 inch diameter)	1·00 to 2·00

Ordinary earthy soils can, however, stand without erosion a velocity of from 2 to 3 feet per second, and stiff soils one of 4 feet per second; the higher the velocity, the less will be the silting.

(c) *Flushing the Canal.*—The amount of silt which water can transport depends upon its velocity. If the water is turbid and its silt content exceeds this amount, it will deposit the excess; if the water is clear and contains less than this amount, it will pick up silt equivalent to the deficiency. Thus very turbid water should not be admitted, while clear water should be utilised in removing silt previously deposited. The most effective way of thus scouring silt is to pass down large supplies in flushes intermittently as the irregular flow lifts the deposit and then carries it on; such supplies need not be confined to very clear water, as a moderate amount of turbidity does not prejudice their action. Flushing can, of course, be overdone so as to cause excessive scour, which may affect the regime of the canal.

(*d*) *Silt-Scouring Fleet.*—The arrangement formerly adopted on the Sirhind Canal in the Punjab consisted of an upper moored barge connected by a cable worked from a winch, with three united lower barges having movable shutters at their stern, which were gradually let downstream. By dropping the shutters of the side barges alternately, the three lower barges swung from side to side and stirred up the silt. The process was, however, not successful, as the heavy bed silt, the removal of which was desired, was again deposited at a short distance from the fleet, owing to the slow velocity of the canal; the finer silt was, however, carried down further by the water. On small native channels in Bombay silt is stirred up by bundles of thorns weighted with stones and drawn by animals, but there the silt is of a fine muddy character, and is transported by the comparatively quick and clear flow.

(*e*) *Silt Escapes.*—These works are intended to get rid of the heavy bed silt which would otherwise remain in the canal. That silt is deposited chiefly in the upper reaches, and the heavier it is, the nearer to the head regulator; gravel will mostly be dropped in the first half-mile, and heavy sand in the first 4 miles, while finer sand may be carried as far as 10 or 12 miles; thereafter there is not much deposit. To be able to act on the whole length affected, the escape should be located downstream of the deposit, but in practice it may be placed not more than one-quarter of the distance upstream of that limit. Its sluices should open from the bottom upwards, so that the bottom water heavily charged with silt may be passed out; *débris* should not be allowed to choke the vents, and their sills should be placed a little below canal bed level to facilitate scour. The pavement of the escape should be made strong, and a water cushion provided downstream of it to resist the heavy action which takes place when the sluices are suddenly opened. The discharge should be into a natural drainage course, as that will be kept clear by the floods due to the run-off from rainfall passing down it; an artificial channel is liable to be choked by the escaped silt and to cause damage to culturable lands.

The working of an escape requires the running to waste of a large amount of water, so that the arrangement is not favoured by some, although others consider it efficient and desirable. It is best, as far as silt removed is concerned, to work with clear water, but unfortunately that is available only at the time when supply is low and the demand for it high. Moderately turbid flow must therefore be utilised, but care should be taken first to analyse its silt content (as this cannot be judged by eye, but should be tested by taking samples of the bed water), and to reject heavily silt-laden water.

(*f*) *Silt Traps.*—Another plan of getting rid of bed silt is to construct silt traps; these have been found effective in dealing with coarse sand deposits in canals with bed-widths not exceeding 40 feet; in wider canals it is difficult to draw the sand to the outlet. A masonry trough is built in the bed of the canal with its bottom sloping in all directions towards an outlet controlled by a sluice. A small extra amount of water is admitted into the canal, and can be utilised in carrying away continuously the bed silt deposited in the trough. As in the case of escapes, the silt traps should be constructed in the length where heavy deposit occurs, and as many as ten should be distributed at intervals of about 500 feet in the centre of that length. They also should discharge into natural watercourses.

(*g*) *Excavation.*—In inundation canals which are dry for half the year, silt is removed by simple excavation and stacked on the sides. There in certain cases after some years it forms such enormous banks that it is found cheaper to excavate new heads rather than to continue deepening the old ones. The expenditure thus incurred on these old works is very great, and will not be lessened until they are remodelled so as to have improved sections and gradients, and are furnished with arrangements for drawing their supplies from clear top water, all of which improvements in modern canals have very considerably reduced the cost of silt removal.

On certain perennially flowing alluvial canals silt is taken out by dredging, which is a costly process.

206. Strengthening Canal Banks by Silting.

(*a*) *General Remarks.*—In the foregoing Articles silt has been regarded as a nuisance, to reduce or get rid of which expenditure and trouble are involved. However, it can be utilised beneficially to strengthen banks which were originally too weak. Such strengthening is required when the bed of the canal is at or a little above or below ground level; when borrow pits outside of it are deep, and thus artificially lower the ground level and induce leakage; when the soil of which the canal bank is made is inferior and porous; and, finally, when the canal is large and a breach of it would cause serious damage and loss. There are three systems by which strengthening by silt can be effected, namely:

(i) The " In and Out " System.
(ii) The " Long Reach " System.
(iii) The " Internal Silting " System.

The two former can be applied to old canals in operation; the last named only to new canals designed with the application of the system in view. Silting can be continued throughout the year, during the flood season by fresh silt from the river, and during the fair season by old silt from the canal picked up by the then clear flow; the latter is the more evenly deposited in the silting reaches. During the fair season supply may not be available for silting, as it entails largely increased loss by evaporation and absorption.

(*b*) *The " In and Out " System.*[1]—In this system banks parallel to the inner canal banks are constructed along the boundaries of the canal property, i.e. as far off as possible, in order to gain greater security, especially at high banks, where, if necessary, an extra width of land should be acquired for the purpose (Art. 233 (*g*)). Cross-banks are formed between the two at intervals, which should depend upon the bed slope of the canal, being increased as the inclination is less, so that the gain in head owing to the slow velocity through the silting compartments compensates for the increased length the water has to traverse in entering, passing through, and leaving them. The spacing of the cross-banks should vary from 500 to 800 feet, and may conveniently be 8 to the mile. These banks should be made by excavating the ground just downstream of them, as afterwards the silting up there will take place most rapidly. Water from the canal is admitted by inlets at the heads of the silting reaches or compartments thus formed, and after passing through them is discharged back into the canal through outlets (Fig. 99).

During the process of silting the safety of the system depends upon the security of the outer banks, and these should therefore be made amply strong. The inner canal banks may be made less strong, but must not be unduly weak, as they will have to withstand the whole pressure of the canal when the silting reaches are empty. The strengthening of the outer banks should therefore be attended to first, then the silting of the bed of the reaches, and lastly the improvement of the canal inner banks; excavated spoil should be distributed accordingly, and care should be taken that it does not interfere with the regularity of the silting.

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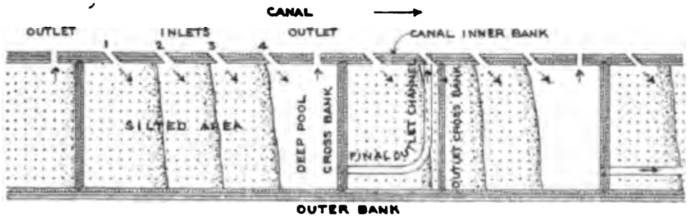
[1] Punjab Irrigation Branch Paper No. 5, by the late A. G. Reid, C.M.G., Punjab Government Press, Lahore, India.

FIG. 99

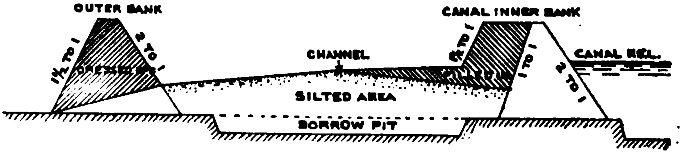
PLAN OF SILTING COMPARTMENTS



The inlets and outlets are open cuts in the canal bank, and should have a bottom-width equal to about one-third of that of the canal up to a maximum of 20 feet, and their bed should be at canal bed level. In order to ensure even silting, it is necessary that their positions should be changed from time to time, and for this reason fixed masonry works for them should not be built. The inlets should have a splay of 45° downstream from the canal, as it has been found that when they are normal to it irregular silt bars form at their downstream ends and choke them. The outlets should be normal to the canal. In their initial position the adjacent inlet of the downstream and the outlet of the upstream compartment should be about 100 feet apart, so that the former may not draw unduly clear water from the upper reach. This inlet should be worked as long as possible, the channel from it being kept open by men stirring up the silt deposit; when that becomes deep, the old inlet should be closed and another similar one opened about 150 feet downstream; this, in its turn, should be replaced by a third. Four successive inlets will probably be enough, as the last will be close to the outlet, which should then be blocked and a fresh outlet opened through the upper part of the silted downstream reach as shown in Fig. 99. Throughout the silting operations care should be taken by diverting the silting channel to get the silt deposited as evenly as possible with a gentle drainage slope from the canal bank outwards, irregularities should be dressed off and the spoil utilised for bank strengthening. Borrow pits should not be excavated in the compartment area subsequent to its formation, as they cannot afterwards be silted up; moreover, this area should be kept free from vegetable growth during the silting, as its presence interferes with the regularity of that process. Finally, the top of the outer bank should be dressed off with a drainage slope to prevent guttering, the cross-banks removed, the surface of the reach trimmed to a slope, and the spoil utilised in filling up the depression of the silt next the canal bank, and in adding to the section of that bank (Fig. 100).

FIG. 100

DRESSING OF SILTING COMPARTMENT



HOR$^{\text{L}}$ TO VERT$^{\text{L}}$ — 1 TO 3

Owing to the draw-off by the inlets, the waterway of the canal becomes too large for its discharge; its velocity is thus reduced, and it deposits its silt, which will not be removed when the inlet is closed. When this reduction of section becomes considerable, the deposit should be dressed off and utilised for bank strengthening. As soon as a reach has been made secure, silting operations on it should be suspended and another reach taken in hand, and so on until the whole length has been attended to, when the completion of the silting of the different reaches can similarly be undertaken. During the operations careful measurements should be taken of the progress of the silting.

The objections to the "in and out" system are the difficulty and expense of getting earth for the cross-banks, and of shifting the inlets and outlets; despite these, it is the most satisfactory and expeditious of all three systems.

(*c*) *The "Long Reach" System.*—This differs from the one just described in that the silting reaches are made from 4,000 to 5,000 feet long, and the whole discharge of the canal, and not portions of it, is passed through them while the canal opposite is closed at head and tail to prevent deposit taking place in it. The efficiency of the operations depends inversely upon the velocity of the water in the reach, and directly upon the quantity of water passed through. As in this case the velocity may be 8 times that of the "in and out" system, the loss of efficiency is considerable, and to this has to be added the difficulty of getting an even deposit of silt down so long a reach. With this system, when the silting is completed, it will be practicable to run the canal discharge alternately down its proper bed and a channel in the long reach, and then to clear the other channel of silt.

(*d*) *The "Internal Silting" System.*—For the application of this a new canal is necessary, and it has to be constructed with an initial waterway much greater than its final one, the reduction to that being effected by the deposit of silt on the bed and banks. As during this process, and especially near its close, the canal is flowing at what should be nearly a non-silting velocity, the rate of deposit is slow. The location of the deposit inside the canal banks is, however, superior to that resulting from the two other systems, where it is outside them. Inside silting is therefore effected only when a small amount of strengthening is required, and is sometimes accelerated by constructing a series of brushwood profiles or groynes to retard the flow and entrap the silt. It is peculiarly adapted to the case of high banks formed of porous soil, which for this purpose should be set well back; so that a good water-tight silt berm may be formed inside them. A further advantage of the system is that it enables the canal bed to be raised nearer ground level than in the case of a work the banks of which are formed of spoil from the excavation of its channel; thus increased command is obtained.

It may be noted that it is not desirable to excavate borrow pits in the bed of the canal to obtain material for the formation of its banks. In the first place the quantity thus obtainable for them is not very great, as the length of each pit should not exceed 1½ times the bed-width of the canal, and there should be unexcavated strips of 10 feet top-width between adjacent pits and unexcavated berms of 6 feet top-width along the toes of the canal banks. Such borrow pits do not silt up quickly, as the water moves down them with not greatly diminished velocity; they cause irregular silting; if the cross-strips breach, retrogression of levels may be caused; and the pools formed by them are dangerous for persons who may attempt to cross the canal.

CHAPTER XVI.

WEIRS ON ALLUVIAL RIVERS.

207. Objects of Weir.

GENERALLY, the main objects to be secured by the construction of a weir are:

(i) To prevent water required for a canal passing the headworks at a level below that at which it can be utilised, and, when the total supply available is all wanted, to arrange that practically none of it flows to waste;
(ii) To raise the level of supply so that it can command by flow the area to be irrigated;
(iii) To gain that command at the cheapest rate by reducing the length and cost of the canal to the minimum, especially those of its head portion in difficult and unirrigable country;
(iv) To reduce the fluctuations of the levels of the river;
(v) To make the control of silt more manageable;
(vi) To render the headworks of the canal permanent, and to prevent them from being prejudicially affected by the vagaries of the river.

In order to gain these advantages almost all modern canals have permanent weirs built at their heads; in certain cases, where the rivers have permanent natural bars and high banks, such artificial structures have not been constructed, but these instances are few and they do not meet the silt difficulty nor make the regulation of supply easy.

208. Selection of Site of Weir.

(*a*) *General Remarks*.—To secure the attainment of the objects mentioned above consideration has to be paid to the following:

(i) General features of the river;
(ii) Detailed features of the river;
(iii) Alignment of the weir;
(iv) Foundations and type of weir;
(v) Height of the weir;
(vi) Availability of materials;
(vii) The irrigable area.

The site selected should have as many as possible of the good features enumerated below, although it will probably not be possible to secure all of them. Sites with dangerous features should, however, not be adopted except after careful deliberation, and when no better alternative ones are available. Some of the remarks in Chapter X on favourable sites for weirs in non-alluvial soils apply to those in alluvial soils.

(*b*) *General Features of the River.*—The general characteristics of a large river are that in its upper part it is of a torrential nature, and ordinarily decreases in its rate of fall until it approaches the sea, when it becomes of a deltaic nature. As the rate of fall decreases, so does the velocity of flow diminish, the material of the bed and that carried down the stream get finer—from boulders to mud—and of a more fertilising nature, and the slopes of the country become gentler both in longitudinal and cross-section.

The higher torrential portions are unsuitable for the location of the headworks of an irrigation scheme on account of the great velocity of the current, and the heavy material carried down, which may be destructive to the works; the latter may have little fertilising value, while the steep slopes of the country may entail extra cost in the construction of the canal. These portions are better fitted for power schemes, as they will allow head to be rapidly obtained, and the velocity which can be attained by giving the supply channel a steep fall will prevent it from becoming blocked by heavy silt.

The upper portions of a river are more subject to sudden high floods than the lower ones where the rise is more gradual. A sudden and large rise greatly increases the effect on a weir as the river channel downstream has not at first time to fill and act as a water cushion protecting the work, nor to reduce the difference in level between the afflux and the downstream flood surface.

(*c*) *Detailed Features of the River.*—In order that the water may have a regular approach to and exit from the weir the river should have a straight course for, say, half a mile both upstream and downstream, and a uniform section, more particularly on the upstream side of the work. The fall of the river should be gentle upstream, so that the backwater storage may be large, and also near the weir downstream, so that the tail velocity may not be great, as that might cause retrogression of levels. Further downstream a steeper fall is desirable, so that the floods may be kept below the canal and the irrigable area. The country upstream of the weir should be well above natural high-flood level, so that even with the afflux produced by the work, long and high flood embankments will not be necessary, and outflanking by the river will not be likely to occur. Downstream of the weir the ground should be above high-flood level, and should have at first a fairly steep longitudinal slope, so as to lessen the length of the head section of the canal in deep cutting.

The width of the river upstream of the weir should not be abnormally great, for if it is, that will lead to irregular silting and the formation of silt islands, which may mask parts of the weir and produce irregular flow over it, and also cross-currents along its upstream face, which may scour the upstream foundations. If that width is abnormally small, the velocity of the flood discharge over the weir will be increased, and will add to the cost of the foundations and to the danger of their failure. If the width downstream is considerable, cross-currents may be produced there; if it is much contracted this implies a steep fall of the bed, the tail discharge will be headed up and the increased velocity may scour the downstream foundations. To reduce the chance of damage to the minimum, the width of the river, both upstream and downstream, at the site of the weir should be normal or slightly less than normal. If silt islands form, they should be dealt with as described at the end of Article 188. A straight natural bar across a wide part of the river forms a good site for the location of a weir, as there the foundations will be high, and the river will have established its own conditions of flow, and these the design of the work should maintain.

The river banks upstream and downstream should be well defined and of a permanent character, so that the course of the river will not be likely to change. A favourable situation for the weir is below the confluence of a main tributary with the river, so that there may be backwater storage up the troughs and margins of each. A tributary flowing generally parallel and near to the river and meeting it below the weir is particularly dangerous, as it may lead to the main stream breaking into it and thus outflanking the work (Art. 182 (*d*)). Another favourable site is one remote from the confluence of the first main tributary downstream with the river, so that the canal crossing of the former will be well above that of the level of the latter, and thus will not be interfered with by its floods.

The finer the silt carried by the river, the slower will be the rate of its deposit in the backwater, as most of it will be carried over the weir by the current. Gravel and large sand are likely to be dropped in the backwater, and may thus very gently diminish its storage contents and interfere with the communication between the canal and the river.

(*d*) *Alignment of the Weir.*—When the bed is sandy, the alignment of the weir should be at right angles to the course of the river, so that it may discharge floods uniformly, and thus not create cross-currents parallel to the weir either upstream or downstream. Such a weir is, moreover, the most economical and practicable, as its rate of flood discharge per foot run will be at a maximum. When the bed is of hard, unerodible material, and especially if it is of rock, some consider an oblique alignment (Art. 30) splaying downstream from the bank on which the canal will be led is preferable in order that a deep channel may be preserved to the canal along the weir; others prefer a reverse alignment sloping upstream. However, such non-normal alignments, besides adding to the length and the cost of the weir, may cause difficulties owing to the irregularity of the flow thus produced; naturally, after the adoption of one of them, it cannot readily be altered to put an end to such difficulties. If it is considered necessary to divert the current of the river to the canal, that might preferably be done by having a right-angled alignment and making the weir crest rise with a gentle longitudinal slope from the canal to the other side. Should this arrangement prove unsatisfactory, the crest levels could easily be altered to remedy the defects produced by their original ones; such adjustment, it is true, might also, but not so easily, be effected in the case of an oblique weir. If boulders and heavy gravel are carried by the river, it is advisable not to deflect the main current towards the canal, but rather to the other bank. When only sand is brought down, there is less objection to making such deflection, as the sand can be dealt with by means of a weir silt trap (Art. 204 (*b*)) ; some, however, prefer that the canal should draw off from as still water as possible.

(*e*) *Foundations and Type of Weir.*—The type of weir to be selected depends upon the nature of the foundations on which it has to be erected. An absolutely solid rock foundation will seldom be available in an alluvial river ; where it occurs, the design of the weir can follow generally that for a work in a non-alluvial river (Chapter X). Where there is fissured rock and the formation extends for a length sufficient to prevent any danger of retrogression of levels, a vertical overfall masonry weir can still be adopted; but in this case its section should be increased in order to secure stability, on the assumption that it is a submerged structure buoyed up by the water passing under it.

Where the foundations are not of this solid character, weirs can nevertheless be constructed, being designed to meet the conditions existing. The three principal types of such weirs are:

(i) A vertical drop weir of masonry with a short impervious apron upstream and a long horizontal masonry floor, or apron, downstream, to prevent scour (Fig. 101) ;

(ii) A masonry slope weir consisting of a short impervious apron upstream, with a very gentle slope of impervious masonry downstream, and having at the summit a weir crest wall to maintain the water level (Fig. 102) ;

(iii) A drystone slope weir similar to (ii), but with the downstream slope constructed of pervious rubble filling (Fig. 103).

Of these (i) is best suited to a firm and fairly impermeable foundation, such as hard clay or solid gravel, and (ii) and (iii) to sandy foundations, which may be of any degree of fineness and porosity, as the design can be modified to suit the conditions. The selection between (ii) and (iii) is governed by the material and labour available ; the former entails the use of cut stone or brickwork in mortar, and the latter of dry rubble of large size and in considerable quantity.

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(*f*) *Height of Weir.*—The height of the weir depends chiefly upon the levels of the canal at the take-off from it, and these, again, upon the elevation of the irrigable area. Other things being equal, a canal starting at a high level will more rapidly gain command, and for a given area under command will be shorter and cheaper and will lose less water in transit than one commencing at a low level. Occasionally the fertile area may be raised so much above the river that to irrigate it a high weir will be required.

Another matter that determines the height of the weir is the necessity for dealing with silt deposit which increases in proportion to the weight and size of the material carried by the river. To remove heavy deposits, and thus to maintain communication between the river and canal, increased scouring power is wanted, and this implies that the undersluice sill should be considerably lower than the canal bed, and therefore that the weir should be high.

The higher the weir the larger the storage capacity of the backwater, but the draw-off of a large canal is so great that no ordinary amount of raising of the weir would secure storage sufficient to tide over a deficient supply in the natural river for a period of considerable duration. However, the larger the backwater capacity, the easier is it to work the canal when the river supply fluctuates.

The objections to high weirs are their greater size and cost, the increased velocity and pressure they produce, intensifying the strain on the works, and the more extended flooding they cause upstream which may entail the construction of expensive protection works. Low weirs are therefore generally preferred for the sake of economy and safety; they may acquire most of the advantages attendant on higher weirs by erecting on them temporary, quick-acting movable crests; this is the solution of the problem usually favoured.

The flanks of the weir and all protective works upstream of it should be raised at least 5 feet above the calculated high-flood level of the afflux.

(*g*) *Availability of Materials.*—As in the case of all large engineering works, the prices at which the materials for construction can be delivered at site much affect the cost of a weir, as their quantities are so great. Where long guide banks form part of the design, the rate at which pitching stone can be obtained is a matter of importance, as considerable supplies may be wanted for construction and also for storage for emergent flood repairs.

(*h*) *The Irrigable Area.*—The culturable land commanded by the weir should be concentrated and situated as near to it as possible, should be of a fertile character, should have gentle slopes, and should not be intersected by considerable cross-drainages. The silt brought down by the river should be of a fertilising nature, so as to reduce the necessity for manure to a minimum; it should be deliverable by the canal on to the fields at a velocity which the ground can stand. Communications and markets should be good.

209. Percolation through Sand.

(*a*) *Classification of Sand.*—Sand which is prevented from escaping forms a reliable foundation, being durable, and only slightly and regularly compressible; but when it can escape, a most unreliable one. If weirs are founded on sand, it is essential to know how the material will behave, and what precautions should be taken when it is subjected to the action of quick-flowing water. Sand is not, however, of one uniform size or character, and therefore it is first necessary to differentiate between different sands. The experiments of Mr. Allen Hazen[1] on the matter are generally accepted as authoritative. He classes mixed sands according to what he terms their "effective size," which he defines as the size of which 10 per cent. by weight of the material is smaller, and 90 per cent. is larger grained. Thus, if 10 per cent. of the sand is of grains less than, and 90 per cent. of grains greater than, 2 millimetres, the "effective size" of the sand is 2 millimetres. Percolation in sand takes place among the individual particles in proportion to the spaces between them, and thus is greater for coarse-grained then for fine-grained varieties. When, however, fine grains are mixed with a coarse-grained sand, the interstitial space of the latter is reduced, and thus the former mainly determine the frictional resistance, the capillary attraction, and the action of the sand generally. Hence in relation to the "effective size" the proportion of fine sand to coarse sand is taken as small. The degree of the porosity of a granular material may be expressed as the fractional part of the mass which consists of open spaces. This part can be determined by the amount of water which can be poured into a box containing the material.

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[1] "Some Physical Properties of Sand and Gravel," by Allen Hazen. Report of Massachusetts State Board of Health, 1892, p. 541.

When a weir is constructed, measures are adopted to prevent, or retard greatly, the passage of water through the sand; as that water is charged with silt, the interstitial spaces are thereby gradually reduced, the "effective size" of the material becomes smaller, and the sand more water-tight and improved from a structural point of view; thus the pressures on the overlying work are lessened. In this respect fine silt is more effective than coarse, both because of its grains being smaller and because they are carried further into the foundation bed of the weir. Both classes have their uses—the coarse sand assists in giving stability, and the fine, impenetrability. In Hazen's formula for sands of "effective size" between 0·10 and 3·0 millimetres diameter (for which only it is considered applicable), the velocity of flow varies directly as the square of their diameter. It also varies directly with the temperature, as water becomes more fluid at high than at low temperatures. Thus under weirs the flow should increase during the hot weather, but probably the variation in discharge is not great, seeing that then the head in the river will be at a minimum. To determine the cross-sectional length to be given to a weir the "effective size" of the local sand should be compared with that of the sand on which existing weirs have been constructed.

Hazen's formula is—

$$V=3{\cdot}28cd^2\frac{h}{l}\left(\frac{t+10}{60}\right)$$

where V is the velocity in feet per 24 hours through the sand;

d, the "effective size" of the sand;

c, a coefficient usually taken as 1,000 for clean sand, and varying from 500 to 700 for dirty sands;

$\frac{h}{l}$, the hydraulic gradient $=\frac{\text{head producing flow}}{\text{length of sand traversed by flow}}$;

t, the temperature of the water in degrees Fahrenheit.

(*b*) *Flow of Water through Sand.*—Theoretical considerations and experiments prove that, when the sectional area and physical conditions of the sand are constant, the percolation discharge—

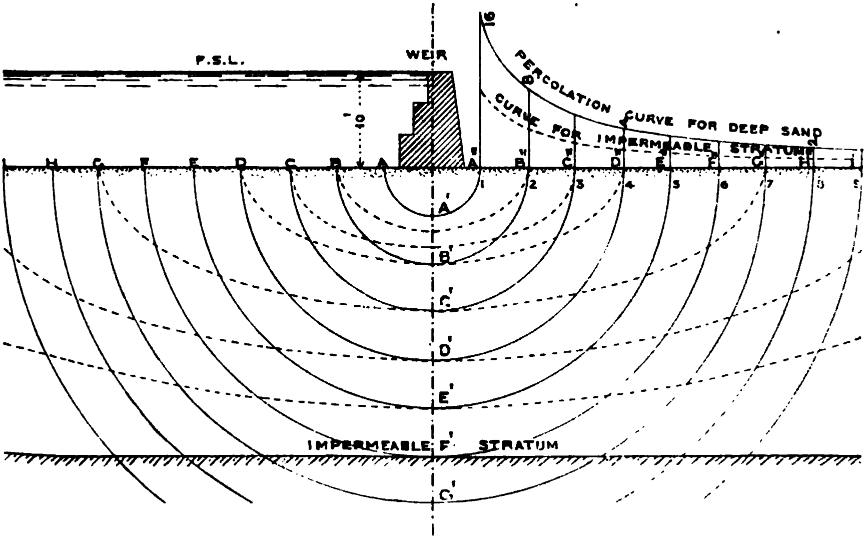
- (i) Through a given length of sand traversed, varies directly as the head of pressure;
- (ii) With a given head of pressure, varies inversely as the length of sand traversed;
- (iii) Other conditions being the same, varies as the sectional area of the sand; and
- (iv) With sands of different degrees of consolidation, or constitution, varies directly with the amount of interstitial space, the resistance to flow being wholly due to surface friction in the mass.

In the case of a weir it cannot be said with certainty what is the extent of subsoil area in its neighbourhood which is affected by the surcharging water.

Under a simple weir wall founded on sand of uniform constitution, the actual flow takes place in concentric semicircular courses struck from the centre of the base, as these are the lines of least resistance,[1] and the percolation must follow

FIG. 104

DIAGRAM OF PERCOLATION UNDER SIMPLE WEIR



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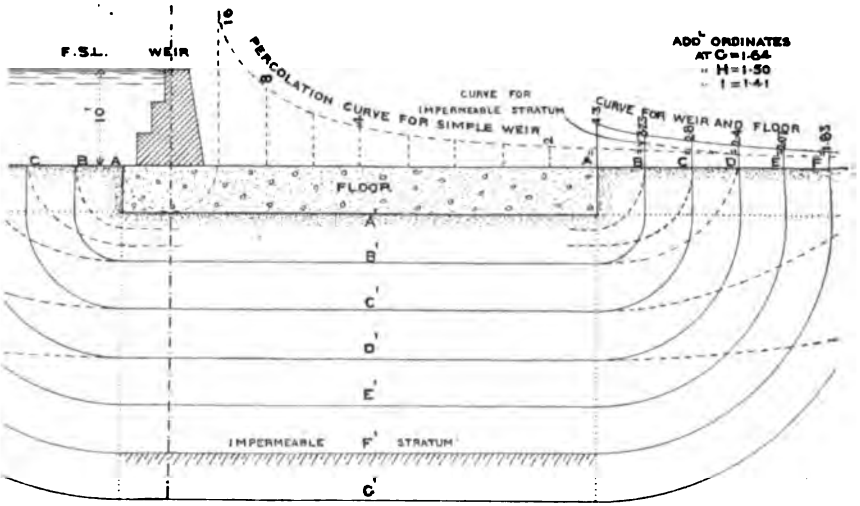
[1] Technical Paper No. 97, Government of India Central Printing Office, Simla, 1902. Note by Mr. J. S. Beresford, C.I.E., M.Inst.C.E., M.E., paras. 8–11.

them, and not occur as intermixed and confused currents. These are shown by full lines in Fig. 104, where the lengths AB, BC, CD, DE, etc., being equal, the lengths of the semicircular courses through them will be in the proportion of 1, 2, 3, 4, etc., and the rates of discharge at their delivery, or tail ends, will be in the proportion of 1, ½, ⅓, ¼, etc. The curve of intensity of percolation at each point is drawn in the Figure on the assumption that the initial intensity is 16 cubic feet in 24 hours per square foot of the horizontal surface of the sand at A″; the area included between this curve and the base line gives the total amount of percolation in 24 hours per running foot of the weir.

FIG. 105

DIAGRAM OF PERCOLATION UNDER WEIR AND FLOOR



When at a moderate depth below the weir there is an impermeable stratum, the semicircular courses become semi-elliptic ones, as shown by dotted lines in the figure. The semi-diameter of the major axis of the ultimate ellipse is the horizontal distance, measured along the surface, of the limit of percolation, and that of its minor axis is the vertical depth below the surface of the impermeable stratum, also limiting percolation; intermediate ellipses have their axes in the same proportion. Both the volume of the sand traversed, and the amount of percolation through it, are thus reduced, the latter in about the proportion of the minor to the major semi-diameters of the ellipses. This shows the great effect such a stratum has in diminishing the amount of subsoil flow.

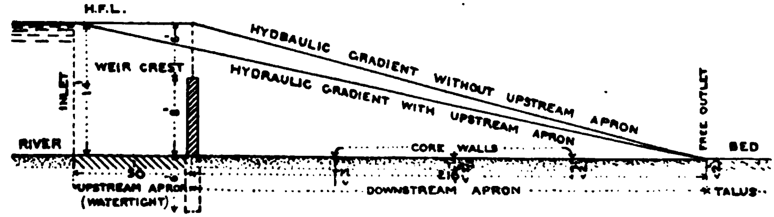
Fig. 105 illustrates the usual case of a weir having a crest wall and floor on the downstream side; here the course of percolation is a combination of the curved lines in the first case and the straight lines under the length of the floor. The percolation curve is drawn as before, and its ordinates are in inverse proportion to those of the first case as are the lengths traversed by the water in the two cases. It will be seen how the overlying floor greatly diminishes the volume of the outflow below the work, and still further reduces the intensity of the percolation. With an additional water-tight apron upstream of the weir, the percolation curve would start from its upstream limit, and would show that by this device the amount of subsoil flow was still further lessened. The full percolation curves in Figs. 104 and 105 are for the worst conditions under which percolation can occur—the usual conditions will tend to reduce it both in intensity and total amount.

(*c*) *Pressure of Water through Sand—Hydraulic Gradient.*—The upward pressure on the overlying foundations of water through sand varies from the full head of the water at the inlet to *nil* at the free outlet; if the material is of uniform constitution, the variation of pressure will also be regular, as shown by the line of pressures in Fig. 106, which is called the "hydraulic gradient." If there are obstructions to the flow of the water, its pressures downstream thereof will be

FIG. 106

HYDRAULIC GRADIENT OF WEIR

HOR^{L} TO VERT^{L}—1 TO 4



decreased, and the hydraulic gradient lowered. In highly porous material the loss of head consumed by the water in traversing it is small, and the *natural* hydraulic gradient is in consequence flat; as the material diminishes in porosity, so do the loss of head and the steepness of the gradient increase (Art. 78). When, however, *artificial* conditions are imposed on the passage of the subsoil water by confining it by an impervious covering, such as a weir, the slope of the hydraulic gradient for any given head depends upon the length of that covering between its inlet upstream and its free outfall downstream. If the inlet and free outfall are far apart, the hydraulic gradient will be flat and the flow through the sand slow; if they are made nearer to each other, the gradient will become steeper and the flow more rapid. Thus the finer the sand underlying a weir, the greater the cross-sectional length which should be given to the work, so that the sand may not be carried away by the subsoil flow.

In all cases the ordinates from points on the base to the hydraulic gradient represent the upward pressures on the base at those points. The design of a weir should therefore secure as low a hydraulic gradient as can be arranged, so as to reduce the pressure on the work. The length of the gradient is governed by the nature of the sand foundations of the locality, and is fixed by the design; the position of the gradient can, however, be adjusted, so that, without altering its total length, but by moving its head upstream of the main work, the portion of its length and the pressures downstream are both decreased. The part of the design by which these advantages are gained is the water-tight apron upstream of the weir (Art. 212), the effect of which is indicated in Fig. 106. It should be noted that this apron produces the greatest reduction of pressures near the weir where relief is most desirable.

The gradients shown are for an impossibly severe condition —high-flood upstream and bed dry downstream. During a flood there is of course tailwater below the weir (and also when a temporary crest impounds water to high-flood level), and this will reduce the upward pressures on the work. Fig. 106 is drawn for the type weir section shown in Fig. 103, by assuming that the length traversed by the percolating subsoil water is equal to the length of the superstructure *plus* twice the depth of the stepping of the foundations. In Fig. 106

the hydraulic gradient for simplicity is shown as a continuous line, but in Fig. 97 it is more correctly drawn as a broken one, with drops corresponding to the falls produced by the individual walls forming the stepping of the foundations.

(*d*) "*Piping*" *and* "*Fountaining*."—The pressure of the water in the sand under a weir acts in two main directions, horizontally and vertically. The horizontal action tends to undermine the weir, and is known as "piping"; the vertical action tends to burst up the floor, and is known as "fountaining."

(i) Piping. This is the more insidious of the two, as it can be developed by the action of the river. If the approach flow to the weir is irregular, currents parallel to it will be produced upstream, and these by scour may cause to be formed under the floor defined channels in which the water will gain increased velocity and pressure. Similarly, the exit flow can scour the sand at the downstream toe of the floor, either by currents parallel to it, or by the direct flow over it, and induce subsoil channels under the floor. When a defined channel under the weir is thus established, the water flowing through it is likely to enlarge it gradually, thereby gaining increased velocity and scouring power until at last it may be able to undermine the work and lead to its failure. This possibly slow and long-continued action may proceed unnoticed while the weir is submerged, and the head on it is considerable. It must be prevented by making the total foundation of the work of ample length, by securing both the upstream and downstream faces from scour, and by cutting off lines of subsoil flow by curtain walls and core walls.

(ii) Fountaining. This may be caused by bad design, whereby the work is made of a thickness insufficient to withstand the upward pressure on it, or by bad construction, whereby water will find its way between defectively bedded courses, and will thus successively lift them and destroy the structure. It may be induced by piping when defined channels are formed, in which the pressure of the water is increased. Fountaining under the upstream apron may be caused by too rapid a lowering of the river level leading to a blowing back of the sand from under it, as the pressure of the water in the sand under the work then diminishes more slowly than in that upstream of it. The maximum pressure on the weir will occur when the backwater is full, and there is no tail flow;

fountaining is then more likely to happen, and as the floor will be dry, can be observed. Its action will, however, probably be very rapid, and then cannot be delayed in time by repairs; but it may stop of itself, when the work will thus be relieved of pressure, and then repairs will have at once to be effected. Probably the most effective measure to take in the case of such an accident is to extend the upstream apron, and make it more water-tight, so as to reduce the pressure downstream of it.

Local fountaining may occur through a vertical joint in the floor; usually this is not a serious matter, as a crater is formed in the underlying sand, and the size of the crater increases, until the velocity of the issuing water is reduced so as no longer to be able to discharge sand. It is generally better not to close such springs when they flow clear, for, if this is done, the water may be forced out at points where a suitable crater will not form. If, however, sand continues to be discharged, the pressure on the work must be reduced and repairs at once effected.

210. General Remarks on Weirs.

(*a*) *Preliminary Remarks.*—A weir being the head of an irrigation system and furnishing its supply, should be a permanent structure, so as to secure the certainty of that supply, and to lessen the risk of its failure; also to obviate the cost and trouble involved by temporary works constructed annually after the flood season has ended. To gain permanency all parts of the weir should be designed to withstand, with a margin for safety, the maximum forces which may act on them. To attain justifiable economy the design should have those parts arranged to resist such forces scientifically with the minimum amount of costly material. Further, as water is a valuable commodity to obtain which is the object of the entire irrigation system, the weir should be made as water-tight as is practicable at a not excessive expenditure. In respect to this it may be noted that although even a considerable increase in the depth of the foundations will not ensure absolute water-tightness on deep sand, the deeper those foundations are carried to a reasonable extent, the less will be the percolation under the weir itself and the safer will it be. The water which will pass under them will then be deep-seated and derived chiefly from the river some distance upstream; its flow will thus not prejudice the safety of the works.

(*b*) *Types of Weirs.*—In Article 208 (*e*) three types of weirs were mentioned, and it was there explained that the two last noticed differed only in the nature of the materials of which they were constructed. Thus from the point of view of design the weirs may be classified as—

(i) Vertical Drop Weirs, and
(ii) Slope Weirs.

Comparing these two with each other, it may be said that (i) is superior to (ii), in that it produces less velocity downstream, and consequently less scour, and thus involves less fear of retrogression of levels; it is, however, inferior in that it causes more pounding action on the tail works and requires better foundations.

(*c*) *Parts of Weirs.*—These two main types each consist of the following parts:

(i) The crest wall;
(ii) The upstream apron;
(iii) The downstream apron;
(iv) The downstream talus.

The main objects of these parts are—(i) To secure the proper level for the canal supply; (ii) to reduce the hydraulic gradient above (iii), and the consequent upward pressure thereon; (iii) to protect (i); and (iv) to render the whole secure from scour. In the following Articles each of these parts for each of the types is described one after the other, so as to compare the variations in their design. The type sections shown in Figs. 101, 102, and 103 are not those of existing weirs, but embody the features of certain of them; the different parts are drawn to show changes of design, and the most appropriate ones can be adopted in any case to suit actual conditions. The sections of numerous constructed weirs are given in Buckley's "The Irrigation Works of India."

As it may become necessary hereafter to raise a weir, it should be designed to permit safely of its being heightened; cases have occurred when weirs not thus constructed have been made higher, and such damage has resulted that they have had to be lowered to their original levels.

211. The Crest Wall.

(*a*) *Pressures to be Resisted.*—The weir wall, being a solid masonry or brickwork construction of some height, can easily resist upward vertical pressure, but it must be designed of ample width so that it can withstand the horizontal pressure of the water upstream, taking into account the fact that, being submerged, it is buoyed up by subsoil water, and thus has its effective weight reduced by the weight of an equivalent volume of water—in other words, the effective weight per cubic foot of masonry will be its own weight less 62·4 lbs., the weight of a cubic foot of water. This consideration is all the more necessary in the case of vertical drop weirs than in that of slope weirs, as the latter are supported by downstream work, whereas the former are not. The slope weir should, however, be strong enough to stand unaided for some time, so that it may not at once be overturned should its downstream apron be partially destroyed.

(*b*) *Deep Foundations.*—Some weirs have been successfully built on very shallow foundations. The Okhla weir on the River Jumna, a drystone slope structure at the head of the Agra Canal, has, in fact, no foundations, although it holds up water to a depth of 10 feet. Shallow foundations may suffice if the river is not subject to sudden and great floods, and if the weir is protected from downstream scour and is not exposed to the action of currents parallel to its upstream and downstream faces. Generally, however, it is better to found the weir to some depth, and, particularly, if within a moderate distance a hard stratum exists, the wall should be founded on it (Fig. 102). The advantages of a deep foundation are that—

It increases the stability of the weir, and thus enables it better to resist overturn when the downstream apron is damaged.

It reduces the amount of flow below the weir.

It lowers the hydraulic gradient on the whole of the works downstream of it, and thus reduces the upward pressure on them, while it does not affect prejudicially the hydraulic gradient and the net downward pressure on the apron upstream of it. Even if by cutting off subsoil flow it raises the gradient upstream, the effect will be only slightly to increase that pressure, and this the foundations of the apron can easily support.

It cuts off leakage planes which might cause piping to occur.

It obviates the necessity for deep foundations for the core walls of the downstream apron.

In India weirs are usually founded on wells built on curbs, and sunk below spring level by excavating their interiors, and by weighting the masonry rings on top (Art. 37 (*d*)). Sinking by the pneumatic process is not economically practicable for a long line of water-tight foundations. The sinking of the wells requires great care to be exercised to ensure that all are vertical and are close to each other. They cannot, however, be sunk so as to be in water-tight connection with one another, and as the long vertical open joints between them might induce piping, these are closed on the upstream side by wooden piles driven so as to form butt joint covers (see plan of Fig. 118, p. 474*a*). Wooden piles by themselves are, however, not so water-tight as wells by themselves, owing to their much greater thinness, more numerous joints, and more perishable nature. In Egypt special cast-iron piles with grooved and tongued joints, cement grouted, have been used successfully.

(*c*) *Continuous Foundations.*—In Egypt the barrages (weirs) are usually founded in open trenches, in areas surrounded by large sand coffer-dams and kept dry by pumping. This secures that the work is all done in the open, which is a great advantage, but the operations are costly. There also barrages have been founded on grouted rubble (Art. 41 (*a*)) laid in dredged trenches. Thus in both cases continuous water-tight barriers have been made, and the subsoil leakage past them is very small. Possibly the sand *in situ* could be grouted to form a similar continuous water-tight foundation by the boring apparatus described in Article 41 (*c*). To reduce leakage below the weir wall the whole of the area below the masonry foundation has been enclosed by longitudinal sheet piling, with lines of cross-piles between them. Although such piling is of a temporary nature, it will last long enough for the foundations of the weir to become waterproofed by river silt carried into its interstices; it may, however, induce piping to take place.

(*d*) *Downstream Batter and Crest.*—The downstream face of a vertical drop weir should have a rectangular batter and not an ogee curve, as that causes the descending water to attain great horizontal velocity, and thus gives it much scouring power on the downstream apron; the simple batter, however, leads to greater horizontal stress on the narrower base of the weir. As certain weirs with ogee curves were destroyed by the overflow, these curves were replaced by plane batters and water cushions. A flat batter is, however, liable to be pounded by the water, and therefore some engineers prefer a vertical face downstream and, if necessary, a battering face upstream (Fig. 101, p. 430*a*).

The velocity of the water over the crest may be great; to resist it very large stones are not necessary, but it is essential that the mortar used should be first class and hard enough to withstand scour. The stones should be built with their longest dimensions parallel to the flow, so that they may better be able to resist removal by the water; the joints should not be too narrow, and should be completely filled by the mortar.

212. The Upstream Apron.

In Article 209 (*c*) it has been explained that the chief object of the upstream apron is to move the crest of the hydraulic gradient upstream, and thus to lessen the height of that gradient and the upward pressure at all points downstream of this apron. The whole length of water-tight apron cannot, however, be placed upstream of the crest wall, as there must be a sufficient length downstream of it to protect that work from scour.

A great economical advantage of the upstream apron is that as it is not exposed to much scour or uplifting action, it need not be formed wholly of expensive masonry. The foundation portion is therefore best made of flexible water-tight clay, say, 2 to 3 feet thick (Fig. 101, p. 430*a*), which lies tight on to the underlying sand, and is pressed on to it by the superincumbent water. As a protection against river scour and aquatic boring creatures, the clay is covered with a layer, say, 2 feet thick, of rubble masonry or concrete blocks; the latter are generally preferred on account of their larger size and greater weight, and should be made substantially monolithic and water-tight by cement grouting the joints. This apron can be laid practically on the surface of the river bed, and being executed in the open, can be formed cheaply, quickly, and soundly. Near the upstream end should be a curtain wall, partly to lower the hydraulic gradient, but chiefly to cut off underground piping channels. The depth of the curtain should be regulated by that of the foundation of the crest wall; if the latter is deep, the former should be shallow, and *vice versâ*, i.e. the foundations of the two should not be on the same horizontal plane, as that might encourage subsoil flow along that plane. The object of sloping the apron up to the crest wall is to prevent eddying motion being created whereby heavy silt will be carried into the canal; the slope also directs flood-borne timber and *débris* over the crest wall.

This apron can be constructed to the same design for all classes of weirs, as the action on it is not affected by the nature of the flow over the weir. Where the foundation is gravelly and thus porous, it may be desirable to aid the upstream apron in staunching subsoil flow by rendering the river bed more water-tight; this may be done by throwing clay on to it above the weir so as to accelerate the natural process of silting up.

213. The Downstream Apron.

(*a*) *General Remarks.*—This portion of the weir protects the crest, or drop, wall and delivers the flood-flow to the river bed downstream with not excessive velocity and scouring power. It is the part which chiefly differentiates the three types of weir (Art. 208 (*e*)). Being subjected to violent water action from above, and to considerable bursting pressure from below, it must be very solidly constructed. Its resistance to upward pressure depends entirely upon its effective weight, which is its own weight less that of the volume of water it displaces. The thickness of the apron should vary from point to point to resist the upward pressure on it, which is in proportion to the height of the hydraulic gradient above the point considered, and should be made, say, 25 per cent. greater than required by theory. Its weight and construction should be such as to prevent any lifting of it from the foundation, whereby, if that occurred, subsoil leakage passages would be formed. Masonry aprons and floors used to be faced with ashlar blocks, but owing to the difficulty of bedding these securely, homogeneous brickwork or rubble masonry, with vertical bond, in cement and laid on concrete, is now preferred for forming the face; for economy the face can be laid on a layer of rubble masonry in lime mortar, and this founded where necessary on a dry rubble mound. Downstream aprons should be built on sand, as if clay is used as a bed for them it may be washed out more easily by piping action.

To localise any damage which may occur, the length of the weir should be separated into bays of, say, 500 feet by "divide walls" running at right angles to the crest wall throughout the downstream apron and its tail works, and these should be securely founded. If it is feared that parallel currents will occur along the toes of the upstream and downstream aprons, these bay divide walls might be extended to beyond both the aprons, so as to direct the river at right angles to and from the weir, and thus prevent the formation of such currents. In Fig. 106A is given a cross-section of the Jhelum weir (which is of the masonry slope type), and this shows both upstream and downstream divide walls.

(*b*) *Vertical Drop Weir.*—In this type the apron takes the form of a flat masonry pavement, or floor, on to which the overfall from the weir pounds. As the action is most severe near the crest wall, this is another reason for increasing the

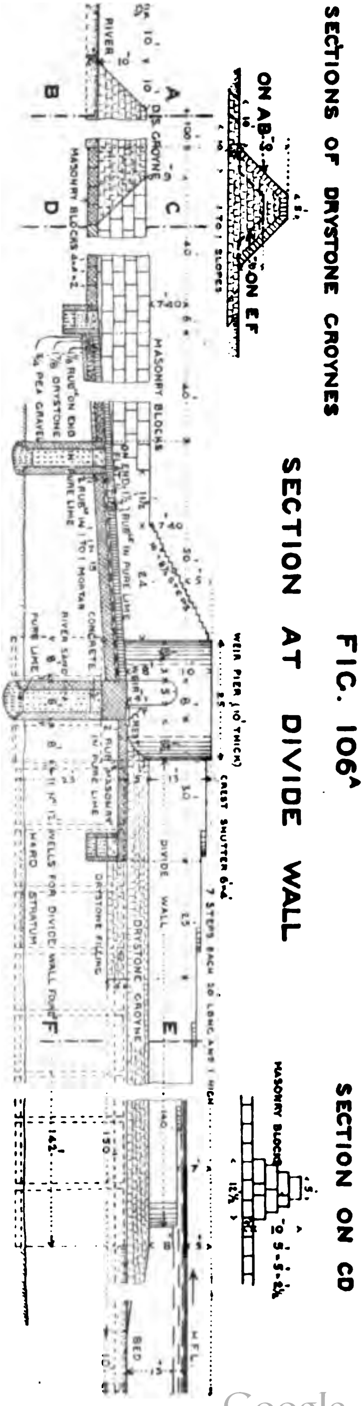


FIG. 106A

SECTION AT DIVIDE WALL

SECTIONS OF DRYSTONE CROYNES

SECTION ON CD

thickness of the pavement there, where it has to be made thick, because the hydraulic gradient is highest over it. The pavement is sometimes constructed with a considerable slope, but this seems a mistake, as such a slope increases the velocity of the water down it, and diminishes the water cushion depth on the upstream part where such protection is most needed. The slope near the crest wall should preferably be sufficient only to secure the drainage of the pavement when there is little or no overfall on it. To make a water cushion over it a low weir wall, say, 3 feet high, is sometimes raised along its downstream margin. This idea might be further developed by building other cross-weir walls between the weir crest wall and the tail wall (as shown by dotted lines in Fig. 101, p. 430*a*), so as to form a series of water cushions which would divide the total fall between them. An objection to this may possibly be that these intermediate weirs may prevent the onward passage of boulders carried over the main weir and cause these to gain a rotatory motion which would have a potholing action on the pavement. Such danger might be obviated by having large vents at intervals in the minor weirs, through which the boulders would be swept, and also, if necessary, low partition walls raised on the divide bay walls parallel to the flow to direct their course.

(*c*) *Masonry Slope Weirs.*—Modern Indian slope weirs have the surfaces of the downstream aprons formed of masonry or brickwork, so that they may resist the action of the water on them ; such protection should be continued to about 30 feet downstream of the lowest position of the standing wave, as down to that point such action will be violent. Instead of uniformly diminishing the thickness of the pavement from crest to tail, that may be constructed in sections each of the same thickness throughout, reductions being made below each core wall, and the thickness of each section being that required by theory at its upstream margin. This will provide a factor of safety, make construction easier, and give equal strength throughout to resist scour. Masonry slopes are preferable to drystone ones, as they withstand scour better and thus require less expenditure on maintenance. A good inclination for the slope is 1 in 15.

(*d*) *Drystone Slope Weirs.*—In this type the whole apron is made of drystone, but the surface of the slope is formed of specially large stones laid vertically with spauls wedged into their interstices to resist scour, as dependence has to be placed solely on the surface, which must therefore be maintained intact by repairs when necessary, although these are costly. Occasionally, when the weir is on fine sand the rubble mound is grouted and the surface formed by a skin of cut stone or concrete blocks; the type then virtually becomes the same as (*c*) above.

It is generally better not to grout the drystone slope, and especially near the downstream end of the apron, as thus a free outlet will be given to the rising percolation water, and the upward pressure on the structure will thus be reduced. The individual stones of the facing must of course be made secure by their weight and fixing against disturbance by the flow of the water over them.

(*e*) .*Core Walls.*—In all three types of weirs it is usual to construct parallel to the crest weir wall a few core walls which with the bay divide walls (end of para. (*a*)) thus form a series of compartments encasing the material of the downstream apron and localising any damage which may occur to it. When a vertical drop weir has the surface of the downstream apron formed below that of the tail river in order to secure a water cushion above it, these compartments during construction can be utilised as coffer-dams to facilitate the building of the body of the apron. In certain works some of these core walls have been made of considerable depth with the object of increasing the length of the path of percolation flow, and thus flattening the hydraulic gradient and reducing the pressures downstream; but this beneficial effect can better be produced by deepening the foundations of the crest wall (Art. 211 (*b*)). The advantages attributed to curtain walls of embankment sluices are noted in Article 201 (*c*), and some depth was then recommended for them, as they are the only cut-off walls there; that depth compared with a weir foundation is, however, but small. For the downstream apron core walls much depth is generally not necessary, as dependence should be placed on the weir crest wall and the curtain wall of the upstream apron to reduce the general volume of percolation. A great depth of foundation for the core walls might possibly, by checking percolation flow, increase the upward bursting pressure upstream. An example of this action was furnished by the failure of the Narora weir, Lower Ganges Canal. Moreover, if the foundations of all the walls throughout the weir are carried to about the same plane, this might induce piping along that plane. It seems better to have irregular (i.e. up-and-down) levels for these foundations and to make the core walls shallow and numerous, rather than deep and few, so that they will cut off piping planes only just below the bed of the apron, where otherwise they might tend to form. Whenever practicable, the foundations should be constructed a year in advance of the superstructures to be raised on them, so that the filling of the excavation trenches may consolidate and become water-tight, and leakage may not take place at them.

(*f*) *Cut-off or Tail Walls.*—At the downstream end of the downstream apron should be a cut-off or tail wall, the object of which is to prevent scour from undermining the apron. With this in view in some cases very deep cut-off walls have been constructed, but as they prevent the percolation water from having a free outlet, they raise the hydraulic gradient above them, and thus increase the pressures throughout the apron. To meet this objection, by making the walls pervious would be to diminish their strength and to increase the chance of piping being induced through them; such piping, can, however, be prevented by constructing a reversed filter upstream of the cut-off wall (Fig. 103, p. 430*a*). A moderate depth (combined with a fair thickness) will give sufficient stability during a temporary damage, and the downstream talus should be designed and relied upon to resist ordinary scour.

214. The Downstream Talus.

This talus is designed to prevent scour from undermining the downstream apron, and at the same time not to interfere with the free outlet of the water percolating below that, as otherwise the hydraulic gradient upstream of it would be raised. This latter condition implies that the talus must not be a continuous, water-tight pavement, and the former one that the separate blocks of which it has therefore to consist must be large, so as to be able to resist the action of floods. As stones of sufficient size would be difficult to handle, it is better to make the talus of blocks of concrete or masonry formed *in situ* as a pavement with close but free joints. It will thus be able to settle if undermined; if extensive settlement takes place, that should be made up by other blocks.

To prevent sand being carried up through the joints, the blocks should be laid on a "reversed filter" layer consisting of fine materials at the bottom and gradually increasing in size to quarry spauls at the top (Fig. 103). At the downstream end of the talus should be a tail or curtain wall of some depth to prevent scour channels forming in the river bed, which would lead to increased scouring action upstream of them. This wall will of course not block the free outlet for the water at the downstream end of the downstream apron, as that is provided by the open joints of the talus. The tail wall might with advantage have its top raised a little above the river bed, so as to form a shallow water cushion which will aid in resisting scour.

215. General Rules for the Design of Weirs.

From the above remarks and those made in Article 209 (*c*) on the hydraulic gradient, the following general rules may be deduced:

(i) The combined lengths of the upstream and downstream aprons (including the crest wall) should be sufficient to prevent the passage of an appreciable flow of water below the weir, thus making it practically water-tight and preventing sand from being carried away from under it. For the sake of safety this total length should not be less than 25 per cent. in excess of what experiment, or the experience derived from other weirs, shows to be the minimum requirement.

(ii) Each part of the weir should be designed to withstand the vertical and horizontal pressures of the water on it, and the action to which it will be subjected; its thickness should be increased at least to 25 per cent. above what theory shows to be necessary. If the length of the hydraulic gradient is reduced, the downstream apron will have to be made thicker to resist the increased upward pressures.

(iii) The impermeable upstream apron should be extended as much as practicable, as thereby the hydraulic gradient and the pressures are decreased downstream.

(iv) The impermeable downstream apron should be of a length sufficient to withstand the scouring action of floods passing over it.

(v) The curtain wall upstream of the upstream apron should be fairly deep, and the foundation of the weir crest of considerable depth, as on it most reliance should be placed for securing stability in case of an accident, and impermeability at all times; the core walls and downstream curtain wall of the downstream apron need then not be of great depth.

(vi) The hydraulic gradient over the works downstream should be lowered as much as possible by impermeable construction upstream, and should not be raised by blocking the free outlet of the water at the downstream end of the impermeable downstream apron or floor.

(vii) Generally, it is better and cheaper to get increased security for the works by an extension of their cross-sectional length rather than of the depths of their foundations.

To these rules may be added another that all parts of the weir, including the river training works, must be maintained in perfect condition by making repairs and additions as soon as they are found to be necessary. For this purpose a careful record of the work should be preserved.

216. Movable Weir Crests.

(*a*) *General Remarks.*—The object of placing a movable crest on the permanent crest of a weir is to secure the maximum fair-weather level required for the canal, and the minimum high-flood level, so as to lessen flooding, the height of flood embankments and the danger of outflanking. When these two levels correspond, the greatest efficiency of the crest is obtained and effect is given to the principle described in Article 28. Another advantage of a movable crest is that it lessens the silting up of the backwater pool, which, if it occurs excessively, may interfere with the supply to the canal. Movable crests are, however, very expensive, and may be difficult to work; as their crest and manipulation increase greatly with their height, in the generality of cases it is advisable to make them low and to depend upon the solid weir to obtain the balance of the elevation necessary. The ultimate development of the movable crest is to make the whole height of the weir movable, and to reduce the masonry practically to a foundation support for the crest.

The nature of the movable crest has to be governed by the conditions of the river; that is to say, when boulders are carried over the weir, or when floods occur often and suddenly, the crests must be different from those which will suffice when only fine silt is passed or when in the fair season there are either no floods or but small, slowly-rising ones, and the crests have not then to be worked frequently. Generally, movable crests should be of simple design (as complication of parts is not only costly, but is liable to cause failure by the entanglement of *débris*), and should be as quick-working as the conditions of the floods necessitate. Where much drift timber may be expected, the bays of the crest should be wide, unless the shutter superstructure can be removed entirely, or the shutters made to lie flat on the weir. The movable crest should work with the smallest amount of shock, and should offer the least obstruction to floods. If not under control, all the shutters should fall simultaneously, otherwise parallel currents may be induced by the irregular flow over the crest, which would then take place.

The working of the movable crest is much facilitated by constructing part of the weir with a low-level ventage sufficient to pass off a small flood when the backwater does not stand higher than the permanent crest. This enables the movable crest to be fixed in the dry, or with only a small flow over the masonry crest, and in time to impound sufficient of the tail of the flood to secure full-supply storage in the backwater. This low-level ventage is given in alluvial weirs by the undersluices, and these do not therefore require to be supplemented by special sluices.

Movable crests [1] may be divided into the following classes:

(i) Fixed vertical shutters;
(ii) Hinged quick-acting shutters;
(iii) Trestle dams; and
(iv) Mechanical dams.

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[1] Several types of movable weirs are illustrated and described by Vernon Harcourt in Paper No. 1665, and by R. B. Buckley, C.S.I., in Paper No. 1670 in Minutes of Proceedings, Inst.C.E., Vol. LX. Figs. 108, 109, and 110 are reproduced from the former, and Figs. 111, 112, and 113, from the latter paper.

(*b*) *Fixed Vertical Shutters*—These can be made to impound water up to 5 feet in height, but 4 feet is a better limit. The simplest form consists of piers, 6 to 10 feet apart, with horizontal planks fixed between them by hand into grooves in the crest and piers; a spacing greater than 10 feet would much increase the difficulty of working. The planks may be united to form more water-tight shutters, and the piers replaced by vertical iron channel joists fitted into cast-iron sockets in the weir crest and supported downstream by removable angle iron struts secured to the crest by lewis bolts (as in Fig. 98, p. 415). A further development is to carry a footway over the piers on an arcade or on girders so that the shutters may be worked by means of a travelling winch running on rails, and during the flood season may be raised above flood level. This arrangement is, however, expensive for the great length of an alluvial weir, and is better adapted to the shorter waste weir of a storage reservoir, for which it forms the cheapest safe method of controlling the high-water levels.

Another simple plan is to have vertical needles supported by horizontal wales between the piers—such a crest can be made staunch by applying, by means of a cup-shaped basket with a long handle, a mixture of sawdust or bran, dry cow-dung and litter to the joints between the needles, into which the water pressure will force them. All these forms of crest can be manipulated only slowly, and they are therefore not adapted to weirs subject to sudden and quickly-rising floods. Unless an overhead footway is provided, the crest has to be removed by hand before floods come, and can be re-erected only when the flood depth does not exceed 18 inches.

(*c*) *Hinged Quick-acting Shutters.*—Such shutters[1] can be erected to store water 8 feet deep, but 6 feet is a better limit. They are made of wrought iron plate stiffened by angles, are hinged at the base, and held upstream by hinged tie rods, which can speedily be lowered either by hand or by means of a wire cable passing alongside the shutters, and having on it a button which engages with a releasing trigger on the downstream side of the shutter as the cable is pulled across the river. The shutters lie flat on the weir crest when floods have to be passed, and can be raised when as much as 4 feet in depth is flowing over the crest. Stones and rubbish carried by floods are liable to lodge under the shutters and tie rods, and thus to interfere with the working of the crest. This type is, however, found in practice to be the most efficient and economical one; to enable it to be worked the crest width of the weir should exceed the height of the shutter by 1 or 2 feet.

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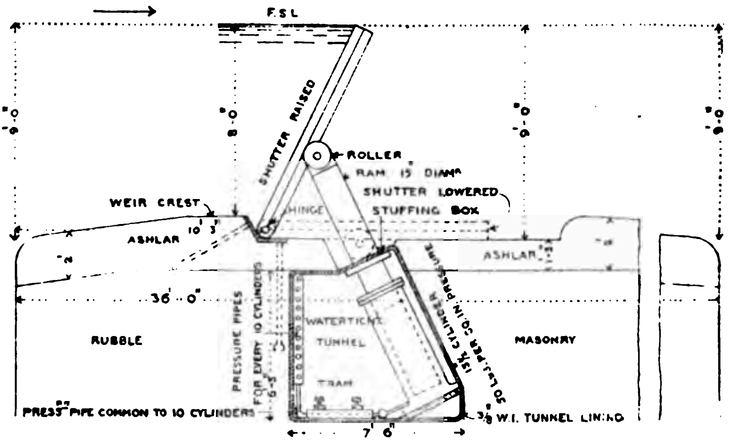
[1] The shutters of this type erected on the Jhelum weir are illustrated in Government of India Technical Paper No. 133, Central Printing Office, Simla.

Another form of hinged shutter, fixed on the Sone weir, Bengal, is made to open automatically by being held by a tie rod pivoted upstream to a casting on the weir, and also to the shutter a little below its full-supply centre of pressure. When the water rises above full-supply level, the shutter, which may be either in one or two pieces, is overbalanced, and falls flat on the weir crest; it is re-erected by hand when the water has fallen to 2½ feet above the crest.

An expensive but reliable form of hinged shutter (Fig. 107) is worked by means of a hydraulic ram, of which the plunger has a roller at its top bearing against the shutter, and is actuated by water under hydraulic pressure conveyed in a pipe in a water-tight tunnel formed below the weir crest. The shutter can thus be raised or lowered when desired, and is under complete control; it can be made so as to store up to 8 feet in depth. The figure illustrates a design for the

FIG. 107

HINGED HYDRAULIC SHUTTER

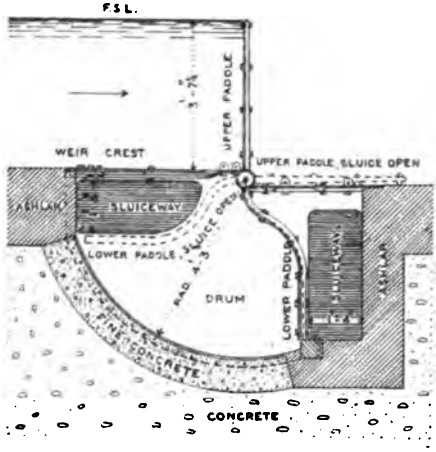


proposed Sukkur Barrage across the Indus in Sind, a work of the first magnitude.

The drum weir (Fig. 108) may be considered to be a form of balanced hinged shutter; it consists of two leaves rigidly connected together and hinged on an axis; the upper leaf stores water on the crest and can be raised or lowered by water pressure admitted to a tunnel under the crest and acting against the lower leaf. This form can be made in lengths up to 200 feet, but its height is small, and probably should not much exceed 3 feet.

FIG. 108

DRUM WEIR

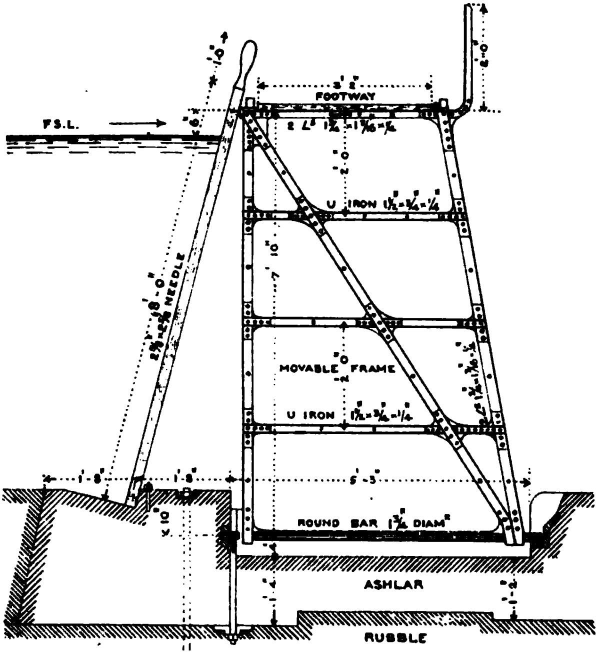


(*d*) *Trestle Weirs.*—This form is of French origin, and has been made to store as much as 20 feet in depth, but about one-half of this is a usual limit. The trestles (Fig. 109) are made of iron and are built up as lattices; they are hinged at the base to the weir crest, to which they are normal, and are preferably spaced apart a distance equal to the depth of water they store, so that they do not overlap each other when lying flat on the crest. When they have to be erected they are hauled up by tackle, and then needles are placed against them; the length and consequent weight of these determine the height of the trestle. Long needles may have to be lifted by machinery; their section, and thus their weight, can be reduced by supporting them by removable wales hung on chains between the trestles. Some high trestles have wooden needles 2 to 3 feet wide stiffened by steel angle irons: these are worked by machinery. Sometimes the trestles support horizontal shutters, and then, on account of the weight of these and the amount of water pressure on them, the trestles have to be spaced closer. The form has not been used in India; it is adapted to the case where there is a considerable depth of water in the river downstream.

(*e*) *Mechanical Weirs.*—(i) These, like trestle weirs, can impound a considerable depth of water, and the weir crest is reduced so much in height as to act only as a foundation for them. Mechanical weirs are very expensive, and they are therefore not constructed in India for the great length of the ordinary weir crest, but are limited to the comparatively small length of the undersluices. They thus form a low-level ventage, which enables the weir movable crest to be raised early, and so as to impound sufficient of the tail of a small flood to secure full storage.

FIG. 109

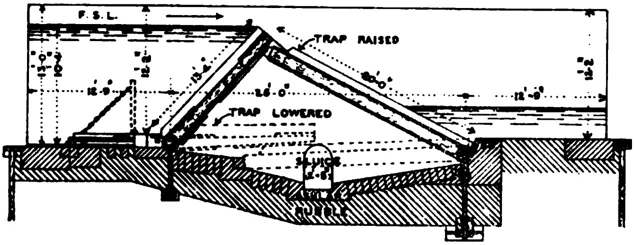
TRESTLE WEIR



(ii) In America a favourite type of mechanical weir is the "Bear Trap," of which there are several varieties. In its simplest form this consists (Fig. 110) of two leaves pivoted at the base and working in a closed chamber; these when raised for securing storage make a triangle with the weir crest. To raise the leaves water is admitted under the downstream one, which is thus lifted and carries the upstream leaf with it ; to lower them a downstream valve in the chamber is opened, and as the water level decreases, the leaves fall and lie flat in a recess on the bed. As the upstream leaf has no upward pressure on it, it is sometimes made in two parts with a loose "idler" covering the upper one to keep out floating *débris* ; in other forms the upstream leaf is jointed. Formerly the leaves were made of wood, but recently they have been built up of iron plates and frames in lengths up to 70 or 80 feet, and are braced to secure rigidity. One objection to the design is its cost, as the total cross-sectional length of the shutters is about three times the storage depth ; another is that there may not be enough natural head available to raise the trap—artificial pressure is then supplied to overcome this defect. Bear traps have, however, been successfully in use for many years, and have not given trouble.

FIG. 110

BEAR TRAP WEIR



(iii) In India several types[1] of quick-acting shutters or gates have been erected for the undersluices of weirs on alluvial rivers. An early form erected in Bengal consists of two wooden shutters strongly hinged at their bases to a large beam (Fig. 111). The shorter shutter is upstream, and is secured by a chain ; the longer one is downstream, and is supported by a sliding strut. When closed to effect storage, the shutters form a V, and are each slightly inclined to the vertical. To close the sluice water is admitted below the upstream shutter and raises it; the downstream shutter is then lifted and secured by hand, and then the upstream shutter falls by its own weight on to the weir crest, and can be kept in place by a catch. To open the sluice the downstream shutter, which alone has retained the storage, is released by disengaging the base of the sliding strut; it then falls flat on the weir crest without shock, as there is always tail water which forms a water cushion to receive it. An objection to the design is the force with which the water pressure acts on the upstream shutter while it is rising, and this is sometimes sufficient to carry it off its hinge.

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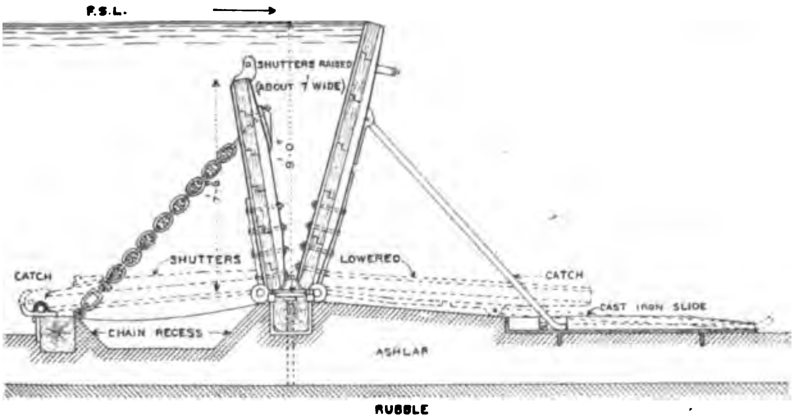
[1] Types of Indian quick-acting shutters are illustrated and described in detail in Buckley's "The Irrigation Works of India," second edition, pp. 183 to 195. Also in his paper on "Movable Dams" in Minutes of Proceedings, Inst.C.E., Vol. LX.

FIG. 111

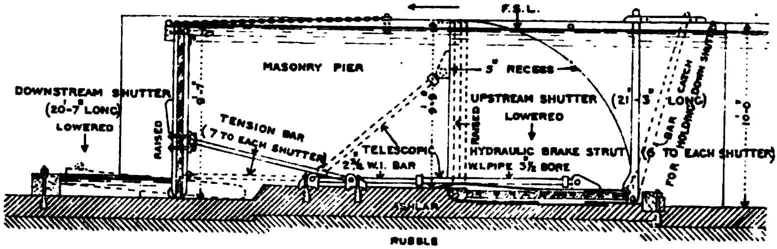
BENGAL UNDERSLUICE



(iv) The Fouracres design is sketched in section in Fig. 112; in it the two shutters rise to vertical positions when fully up, and are some distance apart. The upstream shutter has fitted to it six telescopic struts, which act as hydraulic brakes, preventing too rapid a rise of the shutter; when water is admitted below this shutter it rises and closes the vent. The downstream shutter has hinged to it a few inches below its full-supply centre of pressure seven tension bars, the other ends of which are hinged to the weir crest. After the upstream shutter is closed, the downstream one is raised by tackle and secured in position, and then the upstream shutter is lowered on to the weir crest, and the storage retained by the downstream one alone. When a flood comes the rise of water level overbalances the downstream shutter, and it falls into the recess made for it in the weir crest. Pairs of this shutter have more recently been fitted with hydraulic gear, which enables them to remain closed during small rises of the water above full-supply level caused by waves, etc. ; when this gear is released, the pairs of shutters fall, and thus the position of any of the pairs is under control. The Fouracres shutter can be lifted without shock against a 10-foot head, whereas for other types the maximum head is about 7 feet.

FIG. 112

FOURACRES UNDERSLUICE

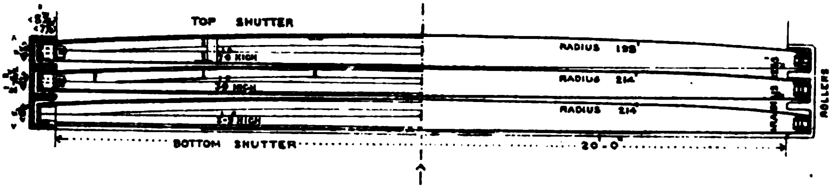

F.S.L.
MASONRY PIER
DOWNSTREAM SHUTTER (20'-7" LONG) LOWERED
RAISED
TENSION BAR (7 TO EACH SHUTTER)
TELESCOPIC 2⅞" W.I. BAR
5" RECESS
UPSTREAM SHUTTER (21'-3" LONG) LOWERED
RAISED
HYDRAULIC BRAKE STRUT (6 TO EACH SHUTTER) W.I. PIPE 3½" BORE
BAR FOR HOLDING DOWN SHUTTER
CATCH
10'-0"
ASHLAR
RUBBLE

(v) Modern weirs have their undersluices made either with two or three built-up wrought iron vertical shutters

FIG. 113

UNDERSLUICE LIFTING SHUTTERS

HALF PLAN THROUGH CENTRES HALF TOP PLAN



placed so that the lower shutter is upstream of the upper one (Fig. 113). The shutters overlap each other about 3 inches to secure water-tightness, and run on rollers in planed and fitted cast-iron grooves built into the piers; chains are fixed on each side of each shutter by means of which they are raised by a traveller running on rails laid on a masonry arcade or girders carried by the undersluice piers, which are themselves pierced by narrow archways to allow of passage along the weir crest. There are several forms of this type; the usual length is 20 feet, and height from 4 to 7½ feet, but shutters on the Smart counterbalanced principle have been made up to 40 feet by 12 feet, and designed up to 80 feet by 9 feet; these are not so effective and easily worked as those made on the well-known Stoney design[1] with bearing rollers mounted in hanging frames. These types are a development of the fixed vertical shutter (*b*). They have the advantages of long spans (allowing flood-borne timber to pass through the sluiceways), of working without shock, and of being completely and easily controlled, so that full-supply storage can always be impounded after a flood has passed. Their disadvantage is that they are slow-acting, but this can be met by arranging for flood warnings being given in time sufficient to allow the shutters to be lowered when necessary. They are also expensive, but the advantage of working from an overhead footway is well worth the cost it entails.

217. Undersluices.

(*a*) *Objects.*—Undersluices are required to bring the river under control as far as is practicable; they are intended to secure the following objects:

- (i) To scour silt deposited in the river bed above the canal head regulator (Art. 204);
- (ii) To preserve a clear channel to that regulator;
- (iii) To facilitate the working of the weir crest (Art. 216 (*e*) (i));
- (iv) To lower the flood level.

(*b*) *Ventage to be Allowed.*—In practice the amount of ventage of the undersluices which is allowed varies considerably in different instances in accordance with local conditions and ideas. The following rules for it have been put forward:

- (i) The ventage of the undersluices below weir crest level to be double that of the head regulator.

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[1] Illustrated in Minutes of Proceedings, Inst.C.E., Vol. LX, Plate 6.

(This presumably is intended to secure what is considered to be sufficient scouring capacity in the approach channel to the undersluices.)

(ii) The ventage to be sufficient to pass the average discharge of the river during the three months immediately succeeding the flood season, when the river backwater stands at weir crest level.

(iii) When the backwater is at full-supply level, the undersluices to be able to discharge the maximum small fair-weather freshet.

(iv) The undersluices at high-flood level to be able to discharge a proportion (varying in actual instances from one-twelfth to one-fifth) of the high-flood discharge of the river.

Of these (i) to (iii) have reference to the scouring capacity of the undersluices, in regard to which it has to be remembered that the silt is deposited by floods having a velocity from 15 to 20 feet a second, whereas it has to be scoured out by a stream which may not have a velocity greater than 6 feet a second. The greater the scouring capacity, the more efficient will be the undersluices; this condition appears to be best fulfilled by (iii), as it permits the utilisation for that purpose of the maximum discharge usefully available. Rule (iv) will probably give a still higher discharging capacity; it is designed to reduce the high-flood level of the backwater that is caused by the obstruction made by the weir, and thus to lessen the depth of flooding, the height of the flood embankments, and the danger of outflanking the works by the river.

At the end of Article 188 it has been noted that the formation of silt islands is evidence that the weir is too long for the ordinary floods of the river, although its length may be required for the discharge of extreme floods. In such a case the proper design would appear to be to have a comparatively short weir to dispose of ordinary floods and a large undersluice ventage to deal with extraordinary ones.

(*c*) *The Position of the Undersluices.*—The undersluices should be placed as close as possible to the canal head regulator; if there are two canals, one on each bank, there should be two sets of undersluices. On the very long Dehri weir for the Sone Canals, Bengal, a third central set was originally constructed in order—

(i) To preserve a navigable channel across the river;
(ii) To lessen silt deposits near the weir; and
(iii) Quickly to fill the river bed downstream to protect the weir talus from scour.

This set has since been closed, as it did not succeed in attaining the first two objects, and the third, which it did secure, was not of great importance. Moreover, it entailed a good deal of regulation of the undersluices during the flood season which it was difficult and dangerous to effect owing to the isolated situation of the work. Had these sluices proved a success in keeping a channel clear across the river, this would have been gained by producing parallel currents, which might have undermined the weir.

(*d*) *Design.*—As the undersluices discharge a very large body of water for a long time, the floor of their downstream apron must be constructed of strong and massive masonry, and must be protected by a long talus with a deep curtain wall downstream. The impermeable upstream apron should be of some length to lessen the hydraulic gradient on the lower works. On the upstream side should be a long divide wall (Fig. 106A, p. 445) to direct the flow of the river to the undersluices, and to form a silt trap (Art. 204 (*b*)). On the downstream side should be another divide wall to protect the weir from the rush of the flood discharge.

The foundations of the piers are subject to great pressure, they usually consist of wells sunk to a depth at least equal to the height of the superstructure. Each pier has to support a thrust equal to the total water pressure on one span of the sluices, and to resist this solely by its own weight; it should therefore be designed so that the resultant of the two forces falls within the middle third of its base. Where there is much drift timber carried down by the river, alternate piers have been designed with their upstream noses long and short, so that each log which strikes the former is deflected down the sluice waterway, and thus is not allowed to float down across it.

The sluices should have their sills at the lowest level practicable (3 feet lower than the sill of the canal head regulator is a good difference), in order to increase their scouring power. The limit of depth will depend on the nature and height of the shutters adopted; some of these have been described shortly in Article 216 (*e*).

(*c*) *Working of Undersluices.*—When the undersluices are open, the large discharge through them carries up heavy silt, some of which would pass into the canal were the head regulator open. As a rule, the undersluices and head regulator should therefore be worked alternately, and not together. If, however, both have to be in action at the same time, the shutters of the former more remote from the latter should alone be opened so as to preserve as much still water as possible near the canal. Every advantage should be taken of small fair-weather freshets to open the undersluices, in order to scour out the silt trap upstream, and during this operation the head regulator should be closed. Similarly, when rain falls on the irrigable area and water is not required for irrigation, the canal should be closed and the undersluices opened.

The larger the undersluices the better can they scour silt, but even the largest ones are sometimes blocked by shingle. The action of large boulders on the floor of the undersluices is very severe, and is a reason for not locating a weir in the boulder section of a river (Art. 208 (*b*)). The heavy discharge through the undersluices tends to draw the river over to them, and thus may make it hug its bank downstream, and endanger the safety of the canal. Possibly this action might be mitigated by slightly splaying and curving the undersluice downstream apron and channel, and lowering their beds towards the centre of the river.

CHAPTER XVII.

CANALS IN ALLUVIAL SOILS—HEAD REGULATORS AND EARTHWORKS.

218. Natural Canal Heads.

In Article 208 (*c*) the most favourable features of sites for weirs on alluvial rivers were described, but there are also canals —chiefly inundation canals—which do not take off from weirs, and have only natural heads or river inlets. The best conditions for these will now be discussed. They relate to—

(i) Permanence of the river and its banks;
(ii) Silting;
(iii) Off-take of the canal head;
(iv) Alignment of the canal;
(v) Starting canal bed level.

(*a*) *Permanence of the River and its Banks.*—A weir secures permanence for the off-take of the canal led off from it; it is seldom that a natural head will offer equally favourable conditions, as the course of an alluvial river is generally liable to change. If such change occurs at the site selected, some or all of its original advantages may be lost, but this contingency has to be faced, and if the worst comes, a new head will have to be constructed. Extensive surveys extending for some miles upstream and downstream should be carried out and continued for some years so as to place on record the liability of the river to change, and, particularly, to indicate the possibility of the formation of a cut-off (Art. 174 (vii)), which, if it occurred, would most likely cause the river to oscillate and to assume an entirely fresh course locally. The annual hydrographic survey of the river should be in detail at all existing canal heads, so as to detect any changes that may be there taking place. Local inquiries should also be made as to the permanence of the natural conditions; as the riparian dwellers are so much interested in the behaviour of the river, their observations will have been carefully taken and are worthy of much consideration—in fact, they may have to be relied on chiefly when time does nor permit of the collection of hydrographic data. The best conditions are when the river, for some length upstream and downstream has a fairly straight course, or only gentle curves, its banks are of hard material, and its velocity is regular, both in longitudinal and cross-section, and is not in excess of what its bed can stand.

(*b*) *Silting.*—As there are no artificial arrangements for preventing the entry of silt into a natural head, it is necessary to see that the natural conditions are favourable to its non-production in excess. For this reason a caving bank must be avoided, as there heavy silt will be produced in the river, and will be deposited in the canal, thus raising its bed, and thereby cutting off its early and late supplies, which are of the utmost importance for irrigation. Such raising is likely to be progressive, as its first effect is to cause the canal to depend more and more for its supply on flood water, bearing heavy silt, and to diminish its flow during low stages of the river, when the water will be clearer and be better able to pick up and carry off previous deposits. This is another illustration of the truth of the adage "silt attracts silt," which was alluded to in Article 202, end of (*b*).

The abstraction by the canal of water from the river has only a slight tendency to affect the regime of the latter by altering its conditions of flow. The volume drawn off by the canal during flood periods, when most silt is in suspension, is, however, generally so small a proportion of the discharge of the river that its withdrawal then will not have practically any effect. The proportion passed down for irrigation will increase as the river decreases, but then the silt in suspension will diminish, and thus again the draw-off by itself will not produce much change in the conditions.

A reduction of the velocity of the water as it leaves the river and enters the canal is of much more importance in regard to the silting of the latter when such reduction is large (as it may well be) than the diminution of volume just considered. The silt which was in suspension in the river can then no longer be wholly carried forward by the slower flowing current of the canal, and part of it will at once be deposited in the canal head. If there is not any great retardation in the velocity at entry, the tendency to silt deposit will naturally be small. Cases in which the canal flow is quicker than that of the river are few; where they occur there will be a tendency for the water to erode the bank of the latter for a short distance until the increased velocity induced in its current is dissipated upstream by its relatively larger volume; the erosion can easily be prevented by a small amount of protection of the river bank.

A sudden change of direction of flow at the off-take of the canal from the river will tend to produce silting at the head of the former, as the water has to reduce its velocity and head up in order to accommodate itself to that change.

Changes of level in the river may of course effect the conditions of entry into the canal. The rise and fall due to the progress or cessation of floods cannot be prevented, but will be at a minimum where the river channel is regular, unobstructed, and has a large cross-section. Considerable fluctuations of level due to scouring or silting of the river bed should be avoided by choosing for the off-take of the canal a site where the river channel is fairly stable and its regime is not subject to alteration.

(*c*) *Off-take of the Canal.*—To avoid the unfavourable conditions described above, which are likely to cause silting in the canal head, the off-take should therefore not be at a caving bank or at one against which the main current sets, but from a length of the river where its banks and bed are stable, its course regular, the general regime more or less permanently established, and its normal velocity not greatly in excess of that of the canal. These conditions are best obtainable in an old backwater creek, or old river course, or in a permanent side channel, and in each case near its re-entry into the main river. There the bed will usually be high, and thus less silt will travel along it, the velocity will be low and little silt will be held in suspension, and the banks are likely to be permanent. The objection to selecting such a channel for supplying the canal is that its own head may silt up and discharge down it may thus be cut off. When this happens, the canal can get its water from the tail of the channel until that also silts up and then the site of the off-take will have to be changed.

Many Punjab inundation canals have two heads excavated at favourable places, and frequently miles apart, so that river erosion is not likely to take place simultaneously at each. Only one is in use at a time, and the other is then closed at both ends; should the first fail by silting or erosion, it is closed at the head, and the other opened and utilised. This is a good arrangement for securing continuity of supply, a matter of the greatest importance, and may possibly prove economical in silt clearance.

The cross-section of the flood waterway of the canal head should be as small as possible, so as to admit the minimum amount of water and lessen its stagnation and the consequent deposit of silt. For this reason the side banks should be placed as close as practicable to the canal.

(*d*) *Alignment of the Canal Head.*—The old Arab engineers aligned their inundation canal heads in Egypt on the following principles:

(i) The off-take to be on the bank against which the deep channel flows;
(ii) Where the river course is curved, the canal head to be aligned tangentially to the general curve of the main current;
(iii) Where the river course is straight, the canal head to be at an acute angle with it;
(iv) The canal not to be taken off where a bar is forming in the river bed.

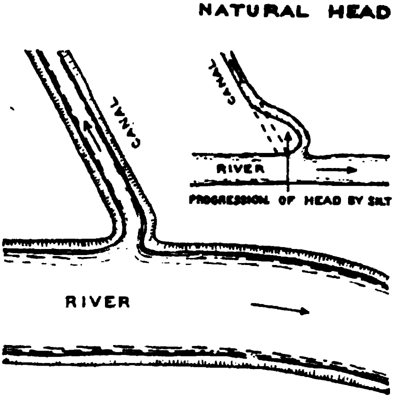
It is believed modern engineers in Egypt do not hold with (i), (ii), and (iii), as nearly all the old canals constructed in accordance therewith silt considerably.

In regard to (i) it may be said that if the main current follows the deep channel, as it usually will, the great velocity there makes the site unsuitable. If, however, there is a deep side trough in the bed upstream and out of the main current, that will be a favourable site. During low water bed silt will be deposited in the trough, and during high water it will be scoured out and the depth restored, so that a natural silt trap will be secured.

With respect to (ii) and (iii), experience gained in Sind is in favour of aligning the canal at an obtuse angle with the river's course upstream of it when the off-take is from a slow-moving backwater. There, in the flood season, it will not be subject to the ingress of much silt, while during low water the canal will get a good supply flowing directly down it. Where, however, the canal takes off from a section of the river having a velocity in excess of its own, it has there been found advisable to align the canal head in a direction pointing slightly upstream. This alignment is the one frequently assumed naturally by the heads of canals, of branches from the canal, and of watercourses led therefrom (Fig. 114). It apparently is produced by the deposit of silt at the upstream side of the off-take, due to the change of direction of the inflowing water there, causing retardation of velocity, and by erosion by swirls on the downstream side thereof. If, however, this action is allowed to continue unchecked, the silting will prevail over the erosion, and the canal head will eventually be blocked and cease to flow. Until this happens, a large portion of the silt has its onward flow checked at the canal head, and is either deposited there, or is swept forward down the river, and thus the water which enters the canal is comparatively clear, and the silting of its bed downstream is diminished.

FIG. 114

UPSTREAM CANAL HEADS



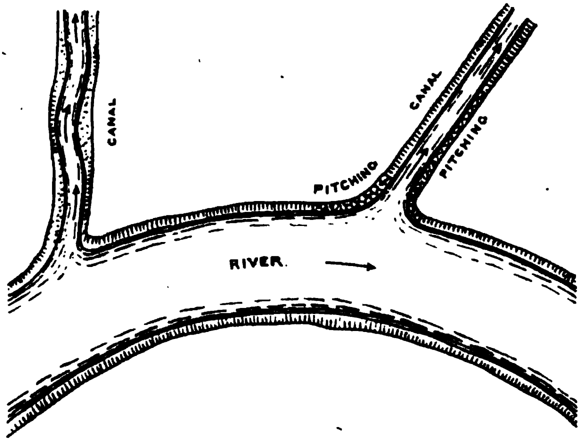
Experience in the Punjab seems similar; there it is considered that an inundation canal should leave the river at an upstream angle somewhat less than 90°, so that the canal may not have an excessive supply forced down it.

When the canal head is aligned to leave the river in a downstream direction and the angle of departure is obtuse, with reference to the river's course upstream of it, the water enters the canal irregularly, and thereafter oscillates from side to side until it can assume steady onward flow. Each oscillation causes silting on its convex side and scour on its concave side, so that the cross-sections of the head are continually changing; this is a condition which tends to cause increased general silting (Fig. 115). If, however, with the same angle of departure the canal head is pitched for a short distance on its upstream side and for a longer distance on its downstream side, the head is permanently held, and the supply passes down the canal regularly without oscillating, so that irregular silting does not take place. Such a head will, however, draw its supply with the river velocity unchecked, and therefore with the burden of silt undiminished. If the canal velocity is sufficient to keep the silt in suspension, it will be carried down and deposited finally on the fields; if that velocity is not high enough, silting of the bed will occur. It may also be noted that if the river is attacking the bank, the presence of a patch of pitching there will aggravate its action by causing swirls to form.

FIG. 115

DOWNSTREAM CANAL HEADS

UNPITCHED PITCHED



The Arab principle, (iv), is obviously correct, for, where a bar is forming, the silt burden of the river is greater than what its velocity can carry, and therefore still more in excess of the transporting power of the slower-moving canal.

The canal head should be aligned as straight as possible, so as to reduce its length to the minimum and to prevent oscillation of flow.

(*e*) *Starting Canal Bed Level.*—The level of the bed at which the canal should start should be fixed with reference both to the surface levels of the irrigated area and the water levels of the river. If the most fertile land is limited in extent, arrangements should first be made to secure its command,

and thereafter the best off-take from the river should be obtained. If, however, the character of the land is uniform, the most suitable off-take should first be selected, and thereafter the canal prolonged to command the extent of area considered desirable to irrigate. The initial canal bed level should be as high above the river bed as practicable (so as to lessen the inflow of bed silt), consistent with an initial canal full-supply level which will be maintained as long as possible throughout the irrigating season, and, in particular, will be sufficient at the beginning and end of that season in order to start the crops early and bring them to maturity. The canal full-supply level should be a foot or two above ground level; if higher than this, the canal embankments may have to be of considerable height; if lower than this, there will be a loss of irrigating command.

(*f*) *Width of Canal Head.*—All heads of canals (and also of branches and distributaries) should be deep and comparatively narrow; a deep channel has a higher velocity and gets an earlier and more prolonged supply than a shallow one. Lower down, where the channel surface is coming to the ground level, the necessary area of waterway may be obtained by widening, so as to reduce the depth to an amount which will be manageable in connection with the canal banks. By such widening the hydraulic gradient, and thus the velocity, at the head can be increased. Where supply is insufficient, the channel should be widened at and above the place of deficiency so as to draw down more water, and the widening should be gradually diminished upstream until it dies out. The head itself should not be widened until it begins to scour on account of the increased velocity. Widening a head unnecessarily in order to increase the supply causes lower down greater expenditure on silt clearance, and the silt deposit shortens the duration of flow in the canal. It must be remembered that the effective supply in a canal is not what it can admit, but what it can pass on. A narrow head can always be widened, but a too wide head cannot well be narrowed, and it will cause silting; in the latter case it is best to deepen the centre of the canal by gently sloping down the bed from the two sides so as to induce these to silt up and the current to flow axially between them. The rule to be observed in canal widening is therefore to work from the tail and proceed upstream, not *vice versâ*.

219. Head Regulators (Fig. 118).

(*a*) *Objects.*—The objects of a head regulator are :

(i) To regulate the supply in the canal ;
(ii) To control the admission of silt into the canal ;
(iii) To shut out river floods from entering the canal.

The regulation of supply is necessary because the demand for water is a fluctuating one depending upon the area under irrigation and the requirements of the crops. Water which is not utilised has to be run to waste, but before this can be done has dropped some of its silt, which will have to be removed without any compensating advantage. Moreover, the supply may have to be shut off entirely after heavy rainfall, when irrigation is unnecessary ; when the canal banks or works have been damaged and have to be repaired ; and when the bed has to be laid dry for silt clearance.

The admission of silt has to be prevented as much as possible, partly by shutting off supply when it is not wanted, but chiefly by drawing off from the river only the clearer top water.

The shutting out of floods has to be effected so that the canal banks and works will not be subjected to the pressure of unduly high water, which might damage or destroy them and thus submerge land, crops, and other property. When there is not a head regulator the canal banks may have to be raised considerably until the excess supply during a flood can be discharged by escapes back into the river, and they are liable to breach and fail under the sudden or extensive rise of the canal surface.

For these reasons a head regulator is a work of the first importance, and as it has to be securely founded and raised to a perfectly safe level, it is also a costly one..

(*b*) *Site of the Regulator.*—The site at which the head regulator should be constructed depends upon the class of the canal to be controlled by it. If the canal takes off from a weir, the regulator should be placed at or near a flank of that work, so that the water approaching the undersluices may sweep past the canal sluices and preserve a clear channel to them. If there is a recess or still backwater space between the two sets of sluices, heavy silting will take place in it, and the entrance to the canal may be partially or wholly blocked thereby. It is usual to place the regulator at the flank of the weir and at right angles to it. Sometimes, in order to secure sounder foundations, or a better alignment or off-take for the head of the canal, the regulator is built separate from and upstream of the weir; in this case, also, it must be placed so that its face is swept free from silt by the current to the undersluices and a clear approach channel to the canal is thus maintained.

If the canal is an inundation one and takes off from the river direct and without a weir, the head regulator has to be located beyond the probable limit of erosion, for if the river attacked it, it would rapidly be destroyed. This may involve an unavoidable retirement of as much as three or even more miles, and for that distance the canal head may be wholly, or partially, submerged during floods, and is liable to be heavily silted by the obstruction formed by the regulator, more especially when that is closed. The design of a silt regulator to reduce the extent of the silting was described in Article 204 (*d*). The site selected for the head regulator should have good foundations, and the ground downstream of it should be favourable for the cheap and safe construction of the canal. The work may have to be connected on both banks with the main river flood embankment, either directly or by junction banks, and this consideration, of course, greatly affects the choice of the site for the regulator.

A good many of the Punjab inundation canals have open heads without regulators. This was the case with all the Sind canals before the British occupation, but now almost all have had head regulators built, and the few remaining will doubtless be supplied with these essentials to their safe and proper working.

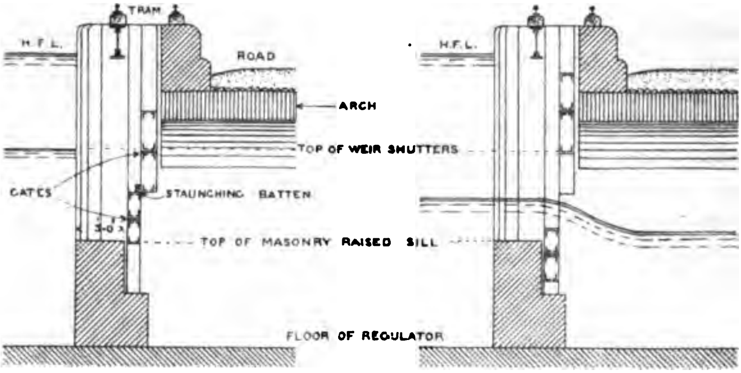
(*c*) *Regulation of Supply.*—The regulation of supply is effected by closing or opening the spans by means of gates, baulks, or needles, as to the relative advantages of which see Article 46. The vents should be worked symmetrically so as to maintain an even axial flow down the canal and not an irregular one, as that might cause oscillations of the discharge which might lead to alternate silting and scouring at the convex and concave bends.

(*d*) *Reduction of Silt.*—The measures which should be taken to reduce silt before admitting supply into the canal have been noted in Article 204. The clear waterway of the head regulator should be large, so that the inlet velocity may not much exceed 3 feet a second, and thus gravel and heavy bed silt will not be stirred up and carried into the canal. A still larger waterway is desirable if there is a probability of the canal having to be enlarged, or if the river keeps low for a long time, or if the inlet channel to the regulator is likely to silt up. To stop the flow of bed silt into the canal the floor of the regulator may be raised, say, for 3 feet or more, so that the bed of the inlet channel will be thus much higher than that of the canal when starting from the work. Instead of raising the whole floor, a raised curtain or breast wall can be built upstream of the sluices, and the bottom gate can be housed just downstream of it to act as a "rising sill," being lowered to open and raised to close (Fig. 116). The upper gate would have a reverse travel in a groove just downstream of that of the former, and, when both were closed, they would completely shut the vent. An objection to such a raised sill is that when the sluices are first opened there is an overfall on to the floor, but by opening them slowly and allowing the canal to fill up, this is not a serious one. Another way of forming a rising sill is to place baulks in grooves upstream of the sluice proper (Fig. 117), so that a water cushion is formed between the two. Ordinarily, gates are made to rise to open; with such the upper gate is raised first so as to admit only top water into the canal.

FIG. 116

GATE RISING SILL

CLOSED PARTLY OPEN

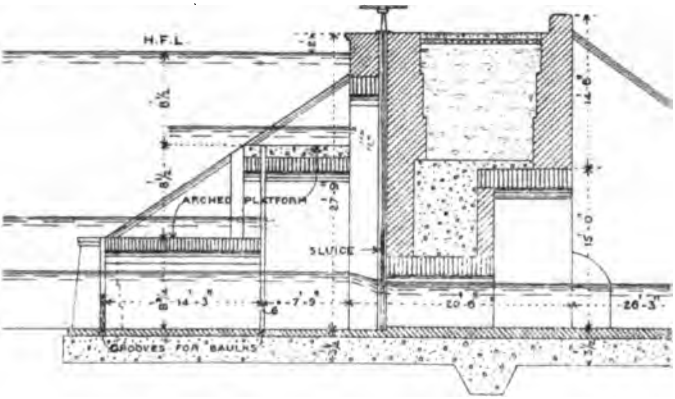


The width of the regulator should be sufficient to pass full supply down the canal when the film of water over the rising sill or closed gate is about 2 feet deep. The consequent increase of the length of the waterway adds to the cost of the regulator, but this extra capital expenditure is justified by the reduction

FIG. 117

BAULK RISING SILL

CROSS SECTION OF HEAD REGULATOR



in maintenance due to less silting and by the more favourable working conditions secured thereby for the canal.

(*e*) *Shutting out of Floods.*—In order that floods may be prevented from entering the canal when the head regulator is closed, its headwall should be carried at least 3 feet above high-flood level. That level should be determined, not only from observation of past floods, but also by a consideration of how the surface may be raised in the future owing to the set of the current, etc. (Art. 176).

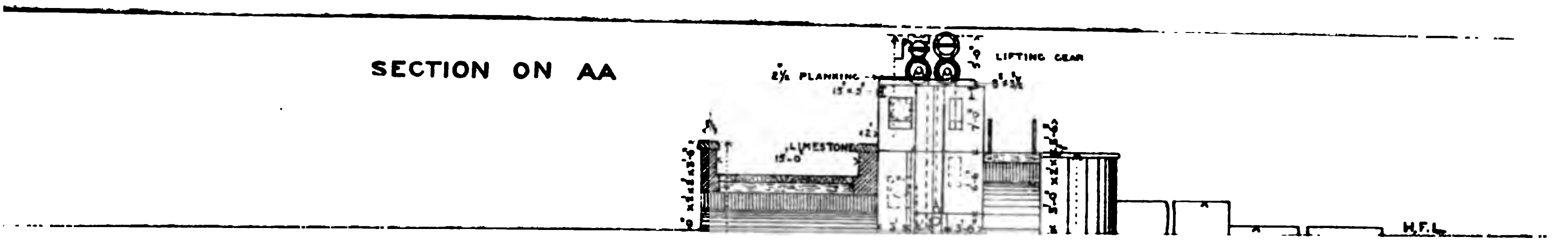
The general seasonal rise of the river is comparatively slow and regular, and thus time is allowed during it to close the regulator as required There are, however, more rapid and fluctuating changes of level at lower stages of the river, and to deal with these properly it is necessary that the regulating apparatus should be fairly quick-acting; from this point of view sluice gates are the best form of regulating apparatus.

(*f*) *Foundations.*—The safety of the work depends greatly upon the sufficiency of its foundations. Although the floor of the head regulator has not to withstand the long-continued and violent flow of floods bringing down heavy detritus and *débris*, as has the floor of the undersluices of a weir, it may be subjected to a greater upward bursting pressure than that has to undergo, for on its upstream side the water may be at river high-flood level, while on the downstream one the canal may be nearly empty; in the case of the undersluices the high-flood levels upstream and downstream do not differ greatly, and the maximum bursting pressure on their floor occurs in the fair weather, when the river upstream is at canal full-supply level and downstream is low.

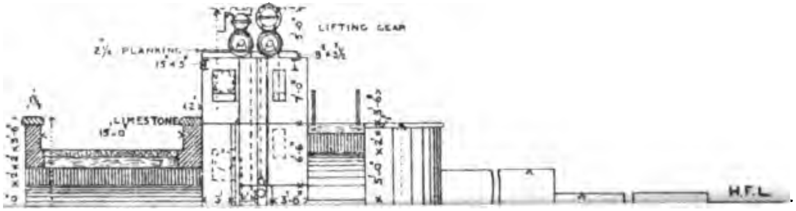
The effect of the hydraulic gradient, as governed by the nature of the subsoil has been discussed in Articles 201 (*b*) and 209 (*c*); the length and thickness of the floor must be ample to resist the pressure which it may have to sustain. The great danger to be feared is piping (Art. 209 (*d*)), to prevent which it is desirable to have deep and impervious curtain walls formed of wells; with their interspaces closed by sheet piles, or, better still as jointless continuous barriers. Upstream of these should be an impermeable apron of thick puddle covered with rubble; if water-lap is feared which would destroy the former, a layer of hard, fine, insoluble material (brick ballast, etc.) should be interposed between the two to prevent this. Downstream of the floor there may be considerable scour due to swirls, and on some inundation canals potholes 20 feet and deeper are formed thereby. To prevent these the downstream apron and talus should be continued for some distance, and should be sloped down as much as the spring level permits, so that the canal may form a water cushion protecting the tail of the works and steadying the flow over that. The bed-width of the canal at the regulator should be gradually reduced downstream to the normal by straight splays, and the sides of the canal protected by brickwork pitching, so as to ensure the steady onward flow of the water.

The portion of the floor between the piers of the regulator may be called the platform; it is subjected to the maximum upward water pressure and to the greatest amount of scouring action; it should therefore be thick and have a hard covering; it should be in good water-tight connection with the pier foundations to prevent piping from occurring there.

SECTION ON AA



SECTION ON AA



The different portions of the floor are therefore—

(i) The impermeable upstream apron;
(ii) The platform with good curtain walls upstream and downstream;
(iii) The downstream impermeable apron;
(iv) The permeable talus with a drop wall downstream to provide against scour.

The piers and abutments require a firm homogeneous foundation as any unequal settlement might affect the working of the regulating apparatus. This is usually provided by forming it with wells either circular or rectangular; the latter, giving a more even bearing, are the better; a continuous foundation, if practicable, would be the best form of all. These foundations, by replacing so much porous subsoil, diminish the subsoil flow. Fig. 118 illustrates a design which has been proposed for the Baghar Canal, Karachi district, Sind, where pitching stone and puddle are not locally available, so that pavements of brick in lime mortar and concrete are substituted for these materials.

(*g*) *Superstructure.*—The superstructure consists of piers supporting arches or girders that carry the roadway of the working deck from which the regulating apparatus is worked.

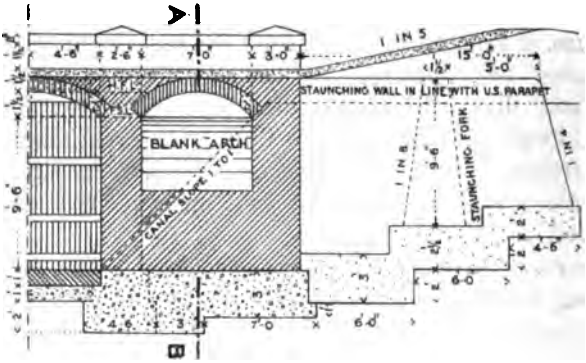
(i) *Piers.*—Each pier has the water pressure concentrated on it from a whole span, and therefore may have to be of a width considerably greater than that necessary for the roadway; the additional width is then given as a buttress on the downstream side. The more numerous the piers the greater has to be the length of the superstructure and the starting bed-width of the canal downstream, both of which are objectionable. Upstream of the regulating apparatus grooves should be cut in the piers, so that in case of accident baulks may be inserted temporarily to block the waterway; the baulks may also be used to form a rising sill.

(ii) *Spans.*—The spans of the arches of old works vary from 5 to 10 feet, being suited to the nature of the closure arrangements—needles, baulks, or sliding gates; in Sind 10 feet is a favourite width. In more modern works spans up to 25 feet have been constructed, and, in the best examples, are closed by Stoney sluices on roller frames; in certain cases where these sluices were not originally fixed the spans were designed for them subsequently, and in the meanwhile were subdivided by jack piers, enabling the waterway to be closed by baulks. Large spans cheapen the cost of the masonry structure, and reduce the number of sluice bearings, which are expensive, but they increase the cost of the sluices themselves and of the lifting apparatus; they enable regulation to be effected more rapidly, which is a great advantage.

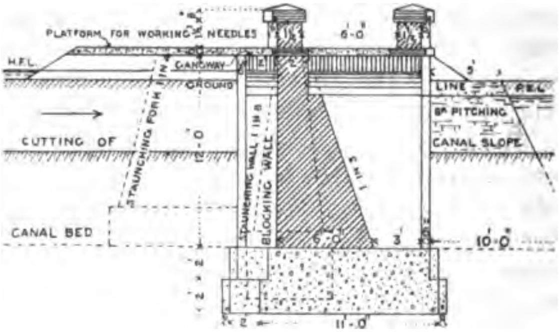
FIG. 119

BLANK ARCH ABUTMENT

LONGITUDINAL SECTION



SECTION ON AB



On all canals, branches, etc., where an extension of waterway is likely to take place in the near future, on account of the development of irrigation, it is advisable to construct one or each abutment of a regulator, etc., as a blank arch closed temporarily by a blocking wall until the removal of that is necessary

(Fig. 119). When such removal is effected, the new abutment can be formed by building a return wall on the downstream side parallel to the staunching wall of the original structure (and that extended as required, to let it act as the upstream return wall), so that the remodelment will entail the smallest amount of pulling down old work and new construction.

Where small sliding gates are used, the springing of the arch should be at canal full-supply level, and one or two horizontal stone lintels should be built across the span to support the top of the frame. In other cases where there are masonry arches the springing is raised so that the arch carries only the roadway; frequently the roadway is borne on girders raised well above the flood level. In such instances the sluices must be able to shut out the highest flood either by their own height or by having baulks placed above them.

The junction of the masonry of the regulator with the flank embankment should be made water-tight by means of a staunching fork.

(iii) *Regulating Apparatus.*—The roadway on top of the regulator must not only be above high-flood level but also must be high enough to permit of any regulating apparatus below it being raised clear of the canal full-supply level. This latter consideration has not to be taken into account where needles or baulks are used, as these are lifted out and stored out of the canal waterway, but it applies to the cases where large sluice gates are fitted. Needles are driven down by a maul, and are raised by a lever working on the parapet wall as a fulcrum. Plain wooden baulks may have to be forced down by blows from a monkey or beam, iron ones descend by their own weight; both kinds are raised by chains and winches or roller windlasses. Small gates are actuated each by their own lifting apparatus, usually a screw, large ones by a winch travelling from one span to another, which makes the regulation slow. (See also Art. 46.)

(iv) *Boat Passage.*—On navigable canals a boat passage has to be provided on the towpath side next the abutment by a span of at least 20 feet in width. In canals where constant communication with the river is unnecessary, this span is closed by needles, baulks, etc., and is opened only when the river surface level permits; where such communication is required, a lock chamber with gates is provided projecting upstream from the regulator.

220. Earthworks.

(*a*) *General Remarks.*—The general considerations which should govern the design and execution of canals have been discussed in Chapter IX, to which reference may be made, and particularly in respect of the matters noted below:

Art. Number.		Page Number.
113	Alignment	233
114	Curves	234
115	Velocity	235
116	Longitudinal slopes	237
117	Side slopes	239
118	Cross-section, depth and bottom-width..	240
119	Full-supply level	241
121	Excavation of the canal	243

The main points in which alluvial canals differ from ordinary non-alluvial ones are their much larger size, the flatter country, and, from the point of view of construction, the inferior soil traversed, and the much larger quantity of silt suspended in the water; the last named has a predominating influence on the design and character of the works (Art. 202).

(*b*) *Silt.*—To deal properly with this the canal should be given as high a velocity as the soil will stand without being scoured, so that all the light suspended silt may be carried on to the fields, and as much as possible of the heavy bed silt may be moved on to the escapes at which it should be passed out. Oscillations of the discharge, irregular flow, and vortices should be prevented, as they cause silt to be deposited ununiformly. For this reason the canal should be set out in long straight lines united by curves of large radius, and the section should be as uniform and regular as practicable. Silt is an evidence either of bad alignment, grading, or incorrect waterway; the defects should be made good quickly, as the deposit has a tendency to increase in amount and in prejudicial effect. Excessive waterway by reducing the velocity causes silting; the proper remedy for this is not the removal of the silt (as if this alone is done fresh deposit will rapidly take its place), but the reduction of the waterway by side groynes of brushwood, etc., at intervals of 100 feet, or as ascertained by experiment, until signs of erosion appear.

(*c*) *Alignment.*—The alignment should get on to the main ridge quickly and thereafter keep on it; cross-drainages should be as few as practicable, for on account of the probable deep foundations and high spring level met with the works are likely to be costly; depressions involving high embankments should be avoided, as also should be areas where the soil is porous, fissured, or charged with salts. The full-supply level should be kept from 1 to 2 feet above ground level so as to secure near command. The depth of the canal should be decreased from head to tail so as to make distribution easier and carry silt on to the fields.

(*d*) *Excavation—Berms.*—In regard to the cross-section to be allowed, as hard substrata are not likely to occur, it is usually not necessary to regulate the depth of excavation on their account—that will be determined by considerations of silting (Art. 203 (*d*)). In alluvial soil the width of berms (Art. 123) has to be made sufficient to prevent undue percolation from the canal and to allow sufficient space for strengthening the banks by silting (Art. 206).

(*e*) *Embankment.*—Some of the remarks made about embankments for non-alluvial canals (Arts. 138 and 139) apply to those for alluvial canals—others do not. The top-width for important canals, and especially where the soil is pervious, should be increased considerably, say up to 6 to 10 feet, but the best precaution to take is to set the banks well back to allow of the formation of wide silt berms. Flat side slopes may also be necessary, particularly where the soil is of pure light sand. Such material is liable to be drifted by the wind, as a protection against which the slopes should, if practicable, be covered with good sweet soil and canal plantations formed as wind breaks. Salt-impregnated soil is bad for the construction of banks, as it absorbs moisture, softens and settles, so that flat slopes are necessary for it. Important canal banks require as careful treatment as do river embankments (Art. 196). The tops of wide banks and berms should be made to slope gently inland so that drainage of rainfall from them may not silt the canal.

221. Silt Clearance.

(*a*) *General Remarks.*—The ordinary operations for the maintenance of a canal have been detailed in Article 111, and such are necessary for canals in alluvial soils; but for them usually the most extensive work is in connection with silt clearance, particularly for inundation canals of small and medium size. Canals from weirs, to a great extent, can have silt controlled before admission (Art. 204), and large and deep inundation canals generally clear themselves, and are less liable to have heavy deposits of silt. The time permissible for silt clearance is often short, and therefore all arrangements should be made beforehand to extend the period as much as practicable, so as thereby to complete the task and diminish the opportunities for fraudulent work and measurement of which advantage might otherwise be taken.

(*b*) *Full-Supply Water-Mark System.*—In Sind the canals are measured out in lengths of 200 feet (each of which is known as a " taki ") ; these are marked at their ends by stout wooden pegs, or distance marks, on the banks, called " taki " pegs. The cross-section of the silt at each taki to be cleared is taken at its taki peg. As a rule, on a heavily silted canal, it is not practicable to work to bedstones fixed in the canal, as it may be difficult to find these, and, anyhow, some time would be lost in waiting until the canal dried sufficiently to clear the overlying silt above them. To obviate this loss of time, the depths to which the silt had to be cleared was originally determined by considering that the bed was a certain depth below the canal full-supply surface, which was therefore marked by small wooden pegs fixed along this line at the end of each taki. Where, however, the regime of a canal is bad, these water marks will not indicate the proper full-supply gradient, and clearance carried out in accordance with them will not result in the attainment of that gradient, but will rather tend to accentuate the errors in the surface longitudinal slope. Moreover, in the case of all canals it is easy to tamper with such water marks, and when this is done, the fraud cannot well be detected subsequently.

(*c*) *" Taki " Stone System.*—The proper system is to settle the depth of silt clearance by reference to the levelled longitudinal section of the canal. For this purpose on each bank levelled stones should be fixed opposite to each other at the end of each taki. Where stones are expensive, cement concrete blocks or large bricks can be substituted; the latter should have a section sufficient for stability, and be overburnt for durability. Each stone should be about 8 inches square in section and at least 2 feet long; it should be firmly embedded in the canal berm for at least 15 inches, and so as to project at least 9 inches above the ground; only the exposed faces need be dressed, the embedded part should be left rough, and should be of as large a section as possible. On top of the stone should be painted, or tarred, its height in feet above the true bed, and on the side facing the canal the number of the taki; this latter might be engraved for the sake of permanence. Where the canal berm is fairly even, all the taki stones can be fixed with their tops at the same height above true canal bed, and then need not have that height marked on them. By stretching a string across each pair of stones, the amount of silt clearance which is to be, or has been, effected can easily and accurately be determined. Where the distance apart of each pair of taki stones exceeds, say, 80 feet, so that there will be a perceptible amount of sag of a string stretched between them, it will be necesary to determine and measure the amount of silt clearance by levelling. As stated above, little clearance will usually be necessary in such large canals.

In order to detect any fraudulent raising of the stones, the whole of them should be levelled over (or tested by boning rods) where such fraud is anticipated, and, anyhow, every two years. To assist this levelling and render it more accurate, permanent benchmarks should be fixed on masonry works on the canal and at intermediate intervals of about a mile on special benchmark stones solidly and immovably bedded. Contract documents should provide for a substantial penalty in cases where taki stones have been raised. The advantages of this system of stones are:

(i) Estimates for clearance can easily be made before the canals are dry;
(ii) Bedstones in the canal are with it unnecessary;
(iii) The measurement and checking of clearance done can easily be effected;
(iv) The actual and true gradients of the canal can be ascertained at any time without the necessity for then levelling its bed;
(v) The levels of the taki stones on the canal bank can be checked at any time.

(*d*) *System of Clearance Estimates and Execution.*—As soon as the extent of silt clearance to be carried out has been settled in respect to its width and bed levels, and with reference to the measurements taken from the taki stones, and the canal is sufficiently dry, excavation profiles of about 18 inches top-width are dug to the determined bed level (which is marked by pegs driven flush therewith) and the spoil thrown on to the canal bed for subsequent removal. To preserve the profiles a narrow strip of unexcavated silt is left on each side of them; their sectional areas are then finally measured and recorded. Before the general excavation is taken in hand all excrescences on the sides and bed, overhanging banks, and other irregularities are removed and finally measured up. (Mounds on the bed are frequently due to fallen branches, etc., which cause an accumulation of silt; canal trees should therefore be trimmed as may be necessary before the irrigation season commences.) The taki lengths between the profiles are then cleared and the excavated silt is stacked neatly at a slope of not less than 1 in 6 at the back of the old spoil banks, so as to leave a clear berm in front of not less than 15 feet width, or is spread where directed. The excavated profiles are left until the work done has been billed for.

Fraud can be committed in three ways:

(i) By raising the beds of the profiles and the tops of the taki stones correspondingly after the contract has been let;
(ii) By clearance to insufficient widths and depths between the profiles;
(iii) By stacking excavated silt in the canal waterway.

Such fraud can be detected—(i) by levelling; (ii) by measurement and the use of boning rods between the profile bed pegs; and (iii) by inspection of the work done. For this purpose 15 per cent. of the cleared takis should be checked independently, the checks recorded in a check measurement book, and the results noted on the bill concerned.

As time is limited and delays may otherwise be purposely incurred in order to get full measurements while the work itself is incomplete, but is submerged by the inflow of inundation water, it is essential to bind contractors to a programme of progress and to keep them up to it by means of weekly progress reports of takis cleared. Their contracts should be terminated at a date which will enable other agency to complete at their expense any unfinished clearance there may be. After that date fresh arrangements are made for executing the balance clearance remaining, which is first measured up and entered in a " deduction measurement book," for recovery of the cost of execution from the original contractor; this work is also checked and the checks recorded similarly to those of the original contract.

(*e*) *Miscellaneous*—(i) "*Gandas.*"—To prevent the entry into an inundation canal under clearance of water due to small pre-inundation rises of the river, the head of the canal is closed by a cross or stop bank, called a " ganda " in Sind. As this has subsequently to be removed, it should be made of the smallest safe section and height, more especially as there will be time to increase these should the rise prove abnormally high. It is necessary, however, to prevent failure of the ganda by water infiltration, and therefore a key trench should be excavated centrally under it from flank to flank; this should be filled with the most water-tight soil locally available, and that should be carefully consolidated.

(ii) *Clearance at Bends.*—Bends on inundation canals are often both numerous and sharp, and at them the silted bed is always tilted from the concave upwards to the convex side. The excavation of the silt should be taken out parallel to the original tilted surface, which, during the subsequent inundation will probably be restored, and not horizontally. Every year some of the worst bends should be flattened to improve the canal regime.

(iii) *Side Slopes.*—As a rule, side slopes are not necessary for silt clearance, and should therefore not be carried out without special orders; these will usually be given where the depth of clearance is considerable.

(iv) *Non-inundation Canals.*—The clearance of these is effected by one or more of the measures described in Article 205.

CHAPTER XVIII.

CANALS IN ALLUVIAL SOILS—REGULATION AND CROSS-DRAINAGE WORKS.

222. General Remarks.

As is the case with canals in non-alluvial soils (Art. 140 (*a*)), canals in alluvial soils have to be provided with regulation and cross-drainage works; the general remarks on the former canals made in that Article apply also to the latter ones. The main differences between the two are that alluvial canals will usually require much deeper and more difficult foundations, as the soil is inferior and the spring level may be high; on account of their large scale the works on them will be mostly of considerable size; the cross-drainage works will be fewer owing to the much flatter and more absorbent country, and for inundation canals in a delta will seldom be wanted; and the effect of silting, both of the canal and drainage waterways, requires to be carefully studied and provided for in the design of the works. The structures will usually be of brick, not stone; where the bricks are porous, precautions will have to be taken to make the construction water-tight, especially the waterway of aqueducts, by cement or hydraulic lime pointing or plastering; where the ground passed through is charged with salts, the bricks should be overburnt to enable them to resist their corrosive action (end of Art. 43).

The works usually constructed, classified under the two heads mentioned, are:

A. Regulation Works.

Art. Number.		Page Number.
223	Cross Regulators	485
224	Outlets	489
225	Falls	494
226	Rapids	500
227	Escapes	504
227 (*d*)	Tail Reservoirs	507

B. Cross-Drainage Works.

Art. Number.		Page Number.
228	Aqueducts	507
229 (*a*)	Superpassages	509
229 (*b*)	Siphons	510
229 (*c*)	Siphon Aqueducts	510
230 (*a*)	Level Crossings	511
230 (*b*)	Inlets..	514

The principles governing the design of these works for alluvial canals are similar to those for non-alluvial canals described in Chapter XI, and therefore only points where the two classes differ need now be mentioned. Particular attention should be paid to providing sufficient high-flood discharging capacity (Art. 150), because the large size of the canals will make extensive the loss due to the failure of any of their works, and because, owing to the flatter slopes of the cross-drainages, abnormal floods may rise proportionately higher in them than in the case of those in non-alluvial country with steeper slopes, or may have greater scouring action on the beds of their channels, or both effects may take place consecutively.

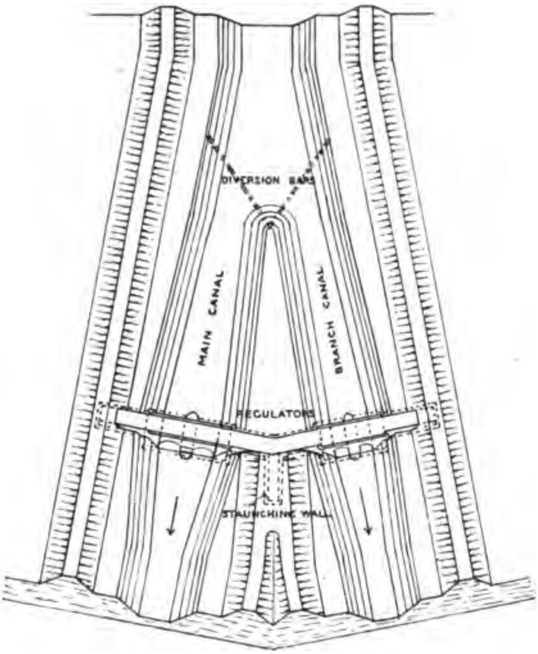
A. REGULATION WORKS.

223. Cross Regulators.

(*a*) *Supply Regulators.*—Regulators are required across the main canal below the bifurcation of branch canals and downstream of escapes and level crossings or to raise the canal level; they are also necessary at the heads of branch canals to regulate their supply. Their general design is similar to that of head regulators, except that, as they have not usually to shut off deep flood water, but only to regulate supplies under control upstream, they are of a lighter character. In regard to branch canals they render it possible to divide properly the supply between them and the lower sections of the main canal; in respect to escapes they compel excess discharge to pass out of the canal; while in the case of level crossings they shut out flood water from entering the canal downstream. It may be desirable on account of silt difficulty not to take a branch off from the main canal at right angles (which is the usual practice), but to make the bifurcation so that each is at a similar small angle with the centre line of the upstream section of the latter (Fig. 120). Further, with the object of lessening silt deposit in the approach channels, it is advisable to bring the two regulators as close as possible to each other, and indeed in continuation of each other, which will have the additional advantage of reducing the cost of separate flank works between them. When this is done in porous, unstable soil, a central staunching wall should be constructed downstream at the bifurcation to prevent a breach occurring when one canal is full and the other empty. If silting above the regulator of the bed of the channel thrown out of use takes place, this may be diminished by diversion bars, as shown in the figure, each such bar being constructed and worked like a silt regulator (Fig. 98, p. 415).

FIG.120

PLAN OF BRANCH REGULATOR



On some old inundation canals in Sind there are large sluices for controlling the supply to considerable proprietary channels, and these are of size intermediate between an ordinary branch regulator and a distributary outlet. They can be designed either as small regulators, or, more cheaply, like river embankment sluices (Fig. 97, p. 400*a*). Occasionally these serve the double purpose of supply inlets and drainage outlets, being opened at the close of the inundation season, when the canal is nearly dry so as to drain back into it the water from the irrigated lands. As that water is clear, it does not cause silting up by its reverse flow.

(*b*) *Level Regulators.*—There is a difference of opinion as to the desirability of having cross regulators constructed solely to raise the level of the canal supply upstream of them. Some hold that not only are they not desirable because of the silting of the bed they induce, but also they are unnecessary because an increased irrigable area can better be obtained by extending the canal. However, it is an axiom (Art. 56 (xix)) that irrigation should be concentrated as much as possible and as near as practicable to the source of supply. The following advantages are claimed in Sind for cross regulators on inundation canals ; some of these apply to branch regulators as well, and others exclusively to level regulators :

(i) They minimise the disadvantages arising from the main canal not being provided with a head regulator.

(ii) They are particularly useful below the heads of large branches, as thereby sufficient supply can be obtained for those branches which otherwise might not be possible when the water level of the main canal is low.

(iii) They allow the main canal to be divided into sections, each of which can be regulated with considerable independence of other sections. With a long, uncontrolled length of canal, proper regulation of distributary discharges is not practicable all down its course.

(iv) They permit the upstream part of the canal to be taken through high ground and to irrigate it, although its downstream part may have to be carried through low ground.

(v) They raise the water level when this is necessary owing to the lowness of the inundation or to excessive draw-off in the upper reaches.

(vi) They raise the water level sufficiently to give a supply by flow to lands only slightly above the natural command of the canal, and for the irrigation of still higher lands reduce the amount of lift.

(vii) They allow the canal upstream of them to be maintained at a higher level than might otherwise be advisable on account of the liability of the banks to breach; when such breaching is feared, the regulator can be opened so as to reduce the level and thus the pressure against these weak places.

(viii) They facilitate the closure of breaches in the lower sections of the canal, and then permit of the utilisation of supply in the upper sections.

(ix) They reduce the liability to flooding of tail lands and utilise in the upper reaches of the canal supply which would otherwise run to waste at the tail.

(x) They permit of the supply being used by branches in rotation, thus economising the expenditure of the whole amount available and preventing waste of water.

(xi) They enable by such a system of rotation the sections of a canal below them to flow for regulated periods with their designed full-supply discharge, despite the fluctuations due to the inundation and to the varying draw-off, and thus diminish the tendency of these lower sections to silt.

(xii) They enable the beds of the heads of branch canals and distributaries to be raised, and these channels to be given a non-silting bed slope, whereby the fertilising fine silt in the supply is carried on to the fields, while the heavy bed silt is kept in the main canal and can be passed out of it at escapes.

(xiii) They lead to a large increase of rabi revenue on canals having a small post-inundation flow.

(xiv) They can be utilised as road bridges, and thus will improve traffic facilities.

There are two disadvantages due to cross regulators:

(i) They put too large a power of regulation into the hands of the lower-paid establishment; the remedy for this is control by time tables of rotation, a constant watch on the canal levels, and inspection of the irrigation by the higher-paid staff.

(ii) They cause silt to be deposited upstream of them; this, however, occurs chiefly when the canal has naturally a small fall; where it has a proper one, the silt deposited during closures is generally washed down the canal, if the regulator is opened for a short time at intervals. In the lower reaches of a canal, where regulators are likely to be most frequent, the supply is usually clearest, and there this temporary silt difficulty is at a minimum.

In Sind it is accepted that cross regulators are of great value on an ordinary perennial canal with a fairly steady discharge and with the admitted silt under control. They should be still more useful on an inundation canal, despite its greater liability to silt, as they will reduce the additional difficulty of distribution due to its fluctuating supply. In California, also, stop planks are used with the object of temporarily raising the naturally deficient canal surface level, and there do not give trouble. The advantages of thus having the surface level of the canal under control as described above will generally outweigh the disadvantages attending temporary silting of the canal bed. The reverse will be the case only when, owing either to the insufficient slope of the canal or to the nature of the silt, the deposits increase with the successive closures, and in the intervals between them are not swept down the canal and out at escapes.

224. Outlets.

(*a*) *General Remarks.*—Outlets are the heads of distributing or field channels from the main distributaries, and are constructed so as to control the supply taken by the actual irrigators; their function is thus similar to that of a regulator of a canal or of one of its main branches. As outlets are very numerous, they have to be constructed cheaply; but as they are also possible sources of great waste, they should be built soundly. On old inundation canals they were originally formed of rough timber, and their vents closed similarly; many of this pattern still exist, although their number is gradually being reduced by the construction of proper sluices. Such rough works have annually to be inspected by the staff as soon as possible after the close of the inundation season, and notices have to be issued to the owners of ones in a dangerous state to put them into good order by a specified time, on penalty of having them closed during the ensuing inundation. To avoid blackmailing it is necessary that the inspection should not be made by temporary low-paid men, and that before repair notices are issued test check inspections should be carried out by superior members of the permanent staff.

(*b*) *Permanent Outlets.*—The earlier form of permanent

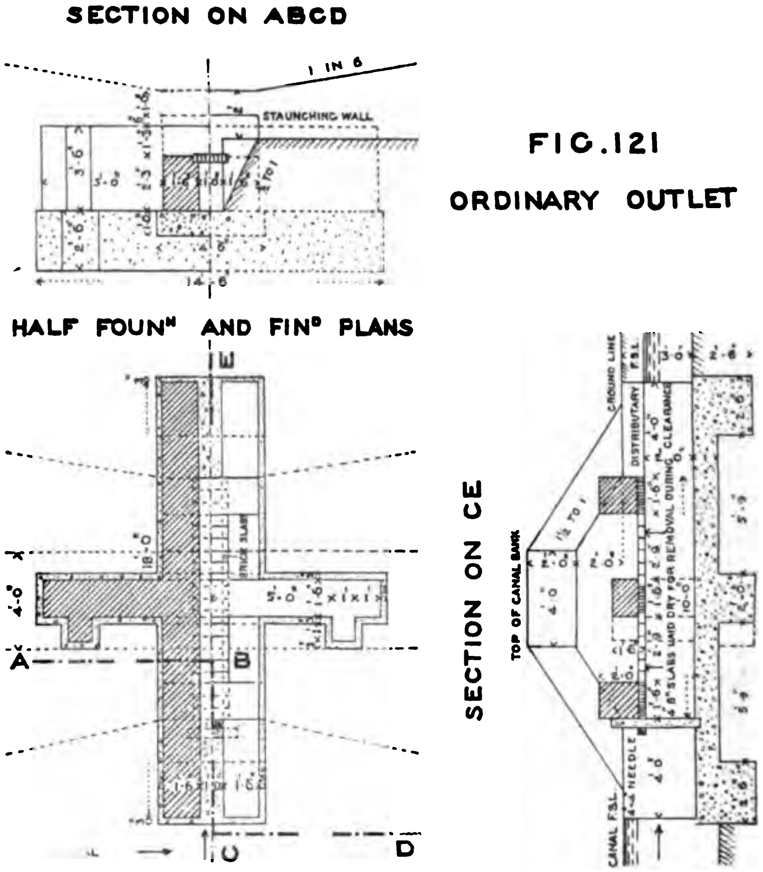


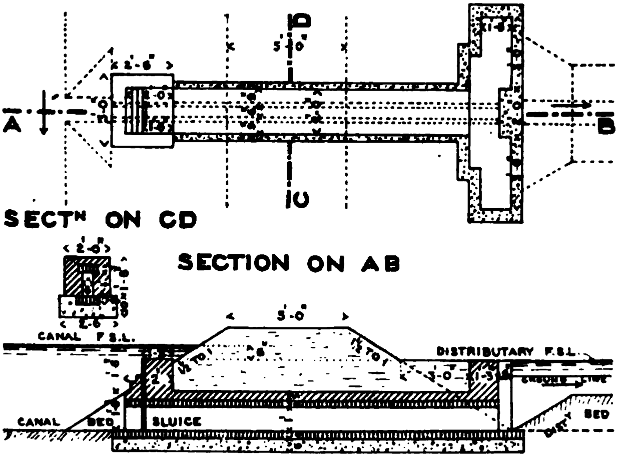
FIG. 121
ORDINARY OUTLET

sluice had its sill constructed at the bed of the field channel and above that of the feeding distributary channel (Fig. 121). By this arrangement only the top water was drawn off, and as the field channel did not take its fair share of the bed silt, the distributary became heavily silted. The later form, originally adopted in the Punjab (Fig. 122), has the sill level with the bed of the feed channel, and the waterway area of the outlet is made small, so that a high velocity is induced through it, which carries a portion of the bed silt of the feeder into the field channel; this pattern has the further advantage that it is cheap. The bed silt is deposited either in the field channel, from which it has to be cleared at intervals, or is passed on to the irrigated lands, which, however, it does not improve unless the soil is heavy. Where escapes for discharging silt are practicable on the main channels, it would therefore seem better thus to get rid of it and somewhat to raise the outlet sills.

FIG. 122

PUNJAB OUTLET

PLAN



(*c*) *Pipe Outlets.*—Small outlets are often made with pipes, instead of slab drains, of diameters varying from 3 to 12 inches, but usually of 6 inches, as the smaller sizes choke with silt (Fig. 123); if a greater discharge is required, two or more pipes are laid side by side. In the Punjab a pipe is ordinarily 0·40 of a foot in diameter, and has therefore an area of 0·125, or one-eighth of a square foot, which is a convenient unit for multiple pipes.

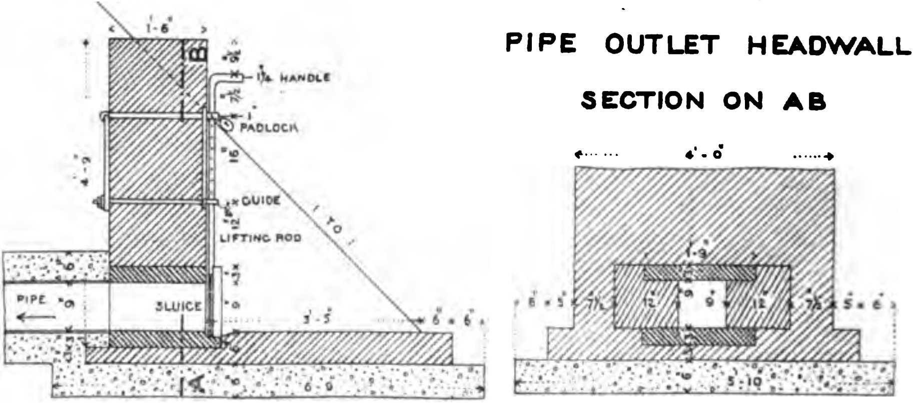
The area of the outlet vent should be proportioned to the extent of land irrigable by the field channel; as the head of that is liable to silt, the vent may be considered to be a drowned orifice, and its size determined accordingly; a small additional head, say, of 6 inches for small or of 1 foot for large channels, should be allowed over the calculated head. Usually, however, empirical allowances are made, and 1 square foot of vent is allowed per 100 acres irrigable, or such area as local experience has shown to be correct.

LONGITUDINAL SECTION

FIG. 123

PIPE OUTLET HEADWALL

SECTION ON AB



Where there is in force a system of supply by a rotation of turns when alone irrigation is permissible, it is necessary that not only should the outlets be of permanent construction, but also that they should be capable of being locked, in order to obtain proper control, unless that control is secured by a regulating sluice supplying a set of outlets (Art. 231 (*c*)).

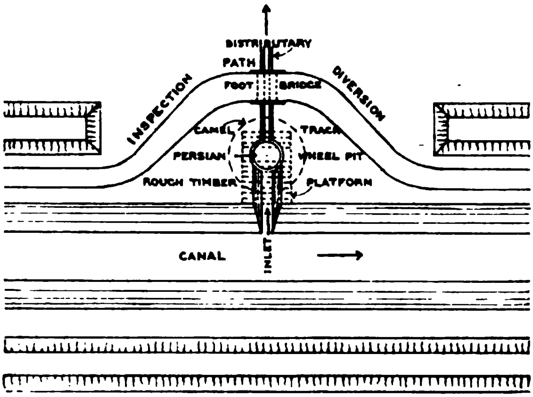
As a rule, outlets should not be constructed on a main channel, as they are a source of weakness, and also it is difficult thus to regulate supply; they should therefore be placed on small distributary branches.

To reduce the cost of an outlet the inspection path of the canal should be led along the inside berm, where the field channel can be crossed cheaply, and not on top of the embankment. To prevent leakage in porous soil outside the outlet vent, that should have a staunching ring constructed around it. When a number of outlets are being built at the same time and the construction can thus be supervised, the foundations, for the sake of economy, can be of concrete; for isolated outlets built with little supervision, the foundations should be of brickwork, to secure soundness.

(*d*) *Lift Irrigation Outlets.*—Another form of outlet is required for lift irrigation, which in Sind is generally carried out by means of a Persian wheel, drawing its supply from a well in the canal inner berm and in communication with the canal by a deep inlet cut. In the old pattern the inspection path was led over this deep cut on a very rough wooden bridge, which was often dangerous for a horse or camel to cross. More recently the path (Fig. 124) has been diverted downstream of the wheel well so as to pass over the shallow outlet channel which can be substantially, although cheaply, done by constructing a small brickwork slab drain for it. A further objection is that, unless the well arrangements are entirely outside the canal waterway, they cause that to silt.

FIG. 124

SINGLE LIFT OUTLET

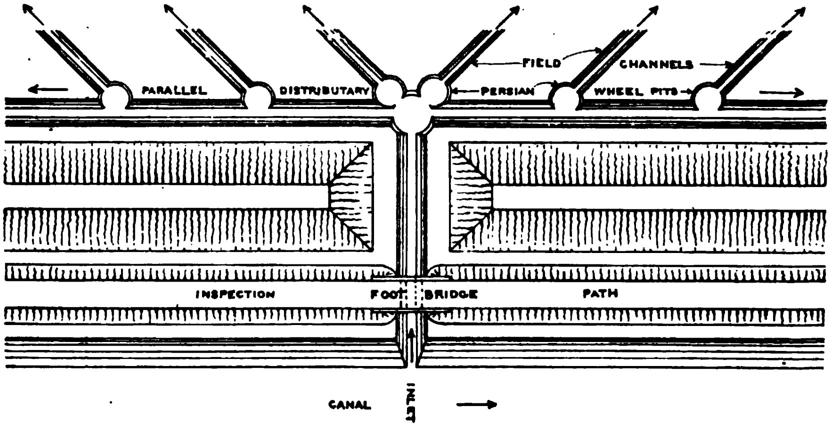


In order to lessen the number of the outlets they have lately been reduced on some canals to two per mile on each bank at selected places. The inlet channel then passes through the canal bank, and downstream of that are constructed the Persian wheel wells supplying the different proprietors' field channels from a distributary parallel to the canal; the wells have their sides lined with brushwood.

The inspection path crosses this common inlet by a masonry footbridge, and the canal bank is stopped short of the inlet channel on both sides (Fig. 125). As lift outlets are generally situated where the ground is higher than canal full-supply level, the berm is usually above water level, and the inspection path on it then does not require to be raised. Should, however, raising be necessary, it will be of much smaller amount

FIG. 125

LIFT OUTLETS IN SERIES



there than what is wanted for the canal bank, so that it will be much cheaper and safer for the inspection path to be led across the inlet channel on the berm, as shown in the figure, than in line with the top of the canal bank, which was the former practice.

The parallel distributary, if long and deep, is likely to silt considerably, and although the irrigators in their desire to get supply will clear it, that is a laborious task which they should not be expected to carry out. The design appears best adapted to cases in which the parallel distributaries will be short and shallow.

It will be noticed that regulating sluices are not provided for lift outlets; the expense of lifting the water is itself sufficient inducement to economise the supply.

225. Falls.

(*a*) *General Remarks.*—In Article 144 were described the general principles affecting the design of falls on non-alluvial canals, and they mostly apply to such works on alluvial canals. On the latter falls are expensive structures, and may give trouble by being undermined by the action of the flow over them, so that, as far as practicable, they should be avoided. A fall near the head of a canal may be an indication that the headworks have been placed too high up the river, but possibly the location of these was fixed by the nature of the sites available, or by the necessity for avoiding the crossing of large drainage lines. Falls are unnecessary when the soils passed through are sufficiently hard to withstand the velocity of flow due to giving the canal a bed slope parallel to the surface of the country. They are necessary when the soils are too soft to resist such velocity, and the canal has consequently to be graded with a bed slope flatter than that surface; also, when extra command has to be obtained upstream, or when the cost of earthwork can be cheapened by introducing them. A fall is required where there is irrigation upstream, as it permits of the regulation of the water level, whereas this cannot usually be effected at rapids which are an alternative means of dealing with a sudden drop; thus falls will chiefly be on the lower reaches of the canal and on its branches. Falls enable the full supply of the canal to be made more parallel to the surface of the country and not too much above it. Above falls branch canals can be taken off with high command; below falls reduction in the depth of the canal can easily be effected. On combined schemes for navigation purposes locks have to be provided at the sites of falls either in direct connection with these or on separate channels; the former arrangement is the better of the two, as it obviates silting of the approach channel to the lock; however, owing to the current thus induced, it adds to the difficulty of navigation.

The following are main principles to be observed in designing falls:

(i) The water approaching the work should do so with its ordinary depth and velocity;

(ii) The water passing over should have its energy destroyed by internal friction on itself, and not by the resistance of the work or the canal section;

(iii) The water should be delivered to the lower reach with a uniform, steady, and gentle onward flow, so that oscillations and swirls will not take place, and erosion and scour will thus be avoided.

(*b*) *Forms of Falls*—(i) *Ogee Fall.*—This was one of the earliest designs constructed; it had on the downstream side a curved masonry slope, which it was hoped would retard the flow by its friction, and deliver the water horizontally to the lower reach. Although the surface of the upper masonry was able to withstand the action of the discharge, it gave the water a high and irregular velocity, which tended to undermine the whole structure, and caused great scour of the canal downstream. To improve matters the design was modified in various ways—by raising the crest so as to reduce the velocity of approach; by advancing the top of the raised crest downstream so as to replace the curve of the top of the ogee by a vertical face; and by building a water cushion wall on the downstream floor. These modifications were not very successful, and the ogee form is now not in favour in India, although it is still built in America.

(ii) *Vertical Fall.*—This resembles the design sketched in Fig. 64, p. 282, but is of a more elaborate description. It is superior to the ogee form, but, like it, delivers the water in an unbroken mass, which has a destructive effect downstream. In some works the crest has been raised above canal bed to lessen the velocity of approach and to reduce to about 4 feet the depth impoundable by the regulating planks, so as to prevent damage downstream through heavy flushes being passed down by their sudden removal. On other works, instead of planks, shutters worked by lifting screws have been used. A raised sill has the disadvantage that if a branch channel is taken off upstream of the fall, it will draw its supply from a silt trap and rapidly get silted.

(iii) *Grating Fall.*—In this design a grating of tapered wooden bars is fixed to the downstream edge of the crest of a vertical fall, so as to break up the sheet of the overfall into a wide series of separate filaments that carry with them much air, which reduces the forward velocity of the water. The bars, with their thin ends downstream, are laid parallel with the flow at an upward slope from the crest of about 1 in 3, and are supported by cross horizontal beams. The taper of the bars has to be calculated so that the surface of the water upstream remains parallel to the canal bed at all depths of flow, consequently there is no acceleration due to the overfall at the weir. This condition is fulfilled by a profile with a flat curve, but in practice the bars are tapered with plane sides. This pattern of notch is a forerunner in wood of the "notch fall" (v) in stone, the principles governing each being the same. The grating fall is a considerable improvement on the earlier types, but suffers in that the grating is liable to be choked by *débris*, and thus to form a solid floor, largely raising the canal level. Another pattern consisted of a grating of horizontal bars laid across the canal downstream of a vertical fall in a series of steps, rising downstream and with spaces between them, through which the water flowed; it apparently was more liable to be choked by *débris*.

(iv) *Timber Falls.*—The simplest form of this type is an overfall weir formed of cribs of rough timber filled with stone. Another pattern suitable only for small falls has a water cushion made by a framed trough. A third is the flash board-fall, which consists of a series of vertical triangular frames erected at intervals across the canal on a wooden floor, which forms the bed of the water cushion. Horizontal flash boards are placed upstream of the frames and are supported by them; their total height can be adjusted as required by adding fresh boards or taking off the top ones. The sides of the channel are protected upstream and downstream by wooden sheeting. The objections to timber falls are that they are formed of perishable material, and are liable to undermining and destruction by the velocity of the water.

(v) *Notch Fall.*[1]—This is the latest form evolved in the Punjab, and successfully meets all the conditions. A design for a large canal is shown in Fig. 126; for large distributaries the dimensions are slightly varied, as noted below:

	Canal.	Distributary.
Distance between plane of profile of centre of notch and the downstream face of the notch wall in feet ..	1·5	0·75
Upstream base curve, radius ½ D in feet	0·5	0·33
Proportion of the thickness of the notch wall with vertical faces to its height	0·5	0·4
Projection of lip at centre of notch in feet	2·0	1·0

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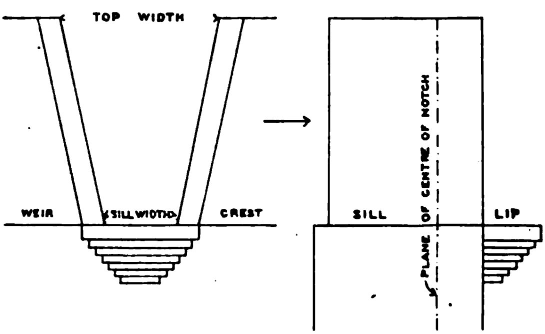
[1] Punjab Irrigation Branch Paper No. 2. Note on Notched Falls by the late A. G. Reid, C.M.G., Punjab Government Press, Lahore, India.

The vent has a horizontal sill and sides inclined at the same angle. Theoretically, as in the case of the "grating fall" ((iii) above), the sides of the notch should have a flat curvature, but, similarly to that, are constructed with plane slopes, which pass through two points calculated respectively for the discharge of the downstream reach at its full-supply level and

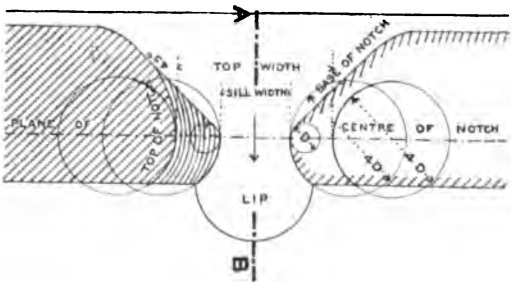
FIG. 126

NOTCH FALL

ELEVATION SECTION ON AB



PLAN



at its least working depth. The curvature arcs are circular, and are struck from centres on the plane of the profile; in plan the upstream splay is 45°, and the downstream splay 22°. The notch walls should be carried 6 inches above high-water level, and the curve of the lips should end at the base of their vertical splay downstream. Good minimum limits for the sill width of the notch are apparently 2 feet for canals and 1½ feet for distributaries ; a rule proposed is that the width of the top of the notch should not exceed its height, but may vary from this to three-quarters of its height. The thickness of the notch piers should not be less than half their height ; it may be more if they have to carry a superstructure, and should be increased to two-thirds of their height if the piers are liable to receive blows from boats or rafted timber. The length of the piers at notch sill level should not be less than their height ; thus the length of the headwall of the notch fall is about twice the total of the mean widths of the notches. The more numerous are the notches, the better is the forward velocity of the discharge checked, but the more expensive is the work ; it is advisable that there should be at least two notches in small and four in medium-sized channels.

The advantages of this form are that at all depths the water approaches the fall at the general level of the canal without acceleration, and leaves it in a series of thin film cascades, which interfere with each other and destroy all excess onward velocity, so that there is steady motion in the tail channel and little tendency to scour. A water cushion is provided to receive the overflow, but need not be deep or long owing to the way the notches break up the sheet of falling water. The expense of this cushion, when the foundations are deep and in water-charged soil, and that of the long superstructure, are the only disadvantages of the design.

(*c*) *Water Cushions.*—These have been dealt with generally in Article 32; here the alignment of their side walls or wings at falls in soft alluvial soils will be discussed. This has to be planned so that the water which cascades over a fall and enters the water cushion with a violent and irregular motion may be made to leave it with an equable and regular flow. If the wings are made to converge considerably, the current will tend to be concentrated along the centre of the tail channel, and may cause scour and irregular flow downstream ; if they are made to diverge considerably, eddies may be produced which may lead to irregular scour and oscillations of the discharge ; if they are first made divergent and then convergent with reversed curves, like the longitudinal section of a soda-water bottle, the initial eddying motion thus produced may not be destroyed at their exit, and similar shaped pools may be formed for some distance down the canal. The best arrangement therefore seems to be to align the wings parallel to the centre line of the canal and to rely on the mass of water with a uniform cross-section in the water cushion to destroy irregularity of flow by its inertia; for this purpose a water cushion should be of some length and of nearly the full width of the canal. If the length proves insufficient, the side walls should be extended as parallel dry rubble training spurs until steady motion is attained. The top of the spurs should be a little below full-supply level at their upstream ends, and should die down to bed level at their downstream ends, so that the canal may silt up behind them. The pavement of the water cushion should be of solid construction, and have a good depth of water over it, so that it may resist the action of the overfall; it should end downstream in a gentle rise, so as not to induce irregular flow, and should have a drop wall at the tail to prevent undermining by scour.

(*d*) *Power Development.*—With the ordinary small drop of a single fall it is usually not economical to develop the water power, but where there may have to be two or more falls close together, it should be possible to do this either by combining these into one high fall, or by leading the water in a pipe from above the uppermost one so as to gain full head at the lowermost one, where a turbine could be placed. The very large Tata hydro-electric scheme in the Western Ghâts above Bombay shows what can be done in this way.

226. Rapids.

(*a*) *General Remarks.*—In Article 145 rapids on non-alluvial canals were described and were illustrated in Fig. 65; on alluvial canals much more elaborate works are necessary, owing to their larger discharge and to the finer soil on which the structures have to be built. Rapids are similar to a series of falls in affording a safe means of descent of some considerable drop, and similar precautions are necessary for both kinds of works in order to prevent too rapid flow to and from them; such large descents should, however, be avoided if practicable. As the control of the canal level upstream is not so easy to effect as in the case of falls, rapids are best placed upstream of the irrigated area; also, from the constructional point of view, this is the best location, as the large amount of boulders required is more likely to be obtained near the head of the canal than lower down its course.

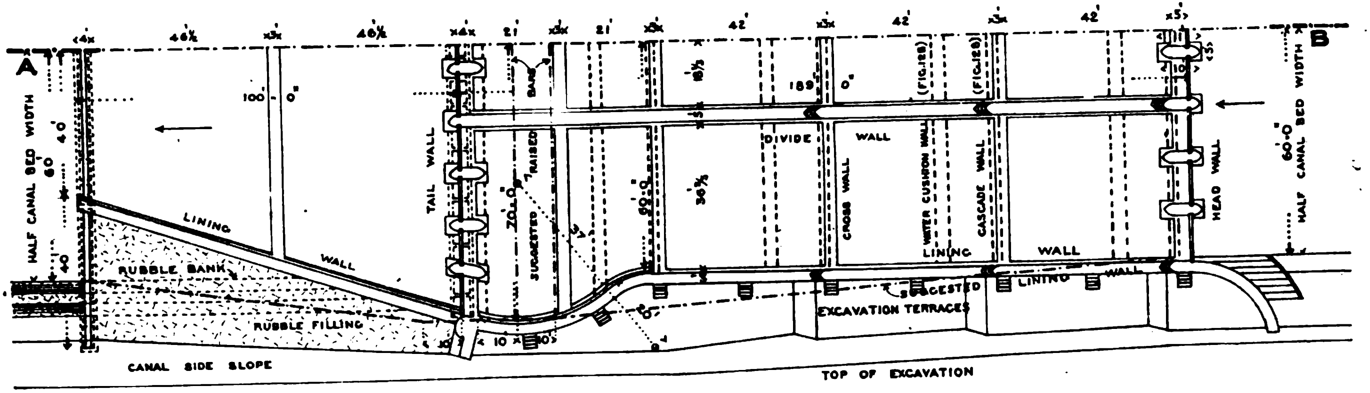
(*b*) *Ordinary Rapids* (Fig. 127).—At the head of the rapid should be a raised masonry bar to check the velocity of approach; piers should be erected on this, and should have grooves and wales for the reception of needles; although these are not often used, they may have to be inserted. The slope of the rapid should vary from 1 in 15 to 1 in 10; a steeper inclination would produce too great a velocity, while a flatter one would unduly increase the length and cost of the works. At intervals of about 40 feet there should be cross and longitudinal masonry walls to form pockets for localising any damage that may occur; the former should be flush with the slope, but the latter may with advantage have their tops raised 2 feet above water level and made approximately parallel to the falling surface. The filling of these pockets should be of single stone hard boulders set on edge, of not less than 80 lbs. each; these if laid dry should be tightly packed together, otherwise they should be set in hydraulic mortar or cement. Some consider that the stones should be brought to an even surface by cement filling in order to prevent jarring due to the impact of the water on projecting heads, which would loosen the stones and cause them to be undermined. Such a surface would not retard the water flowing down the rapid, and it would be delivered at the foot with a high velocity which would produce a considerable standing wave; but it is held that the tail works can be made to resist such violent action there. Others recommend that the tops of the boulders should be left rough, so as to destroy the velocity of the water as much as possible, and this would seem to be the better arrangement; if the loosening by jar and the consequent undermining of the stones is feared, that can be guarded against by packing them securely and laying them on a good layer of quarry spauls, small stones, etc., which will protect the soil bed from being scoured. Soft stones or brick are not sufficiently hard to resist the large amount of scouring action on the slope of a rapid.

The flatter and wider the slope, the more gentle will be the action of the water on it, but the greater will be the cost of the work; this, however, will also depend upon the rate at which the boulders are procurable. Where stones are plentiful and cheap, a gentler slope is permissible than where they are scarce and dear. It has been recommended that for ordinary fine alluvial soils the bed-width of the rapid should be seven-eighths that of the canal, and for hard soils three-quarters

FIG. 127

ORDINARY RAPID

HALF PLAN



SECTION ON AB

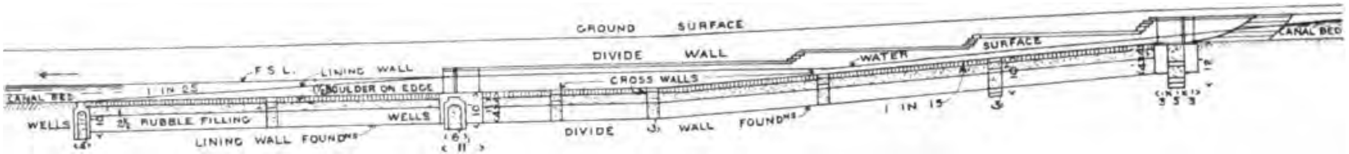
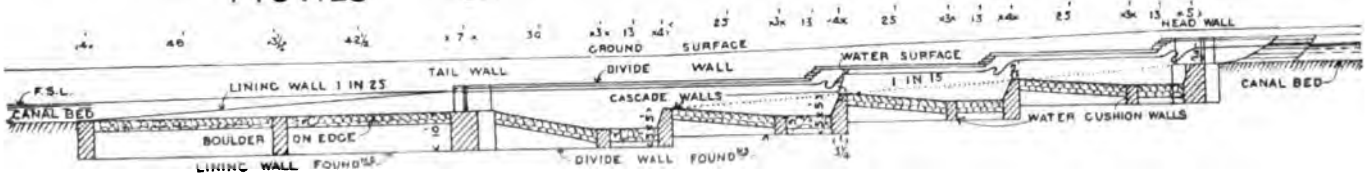


FIG. 128 CASCADE RAPID SECTION ON AB (FIG 127)



of that. It would seem advisable also to take into account the depth of the sheet of rushing water.

At the downstream end of the slope should be a cross-wall, and on this grooved piers can be constructed so that by means of needles a regular delivery of the water may be effected. The tailworks required for the prevention of scour and erosion should be similar to those for falls, although on a smaller scale, as the action at rapids is less violent. The canal banks upstream and downstream should be pitched for considerable lengths to where the flow is of normal velocity.

The figure shows a constructed work with the tail-lining wall splayed to contract the tail flow and direct it centrally down the canal; objection has been raised to this as the concentrated current may produce irregular motion, which may extend downstream of the protective works and damage the canal there. A suggested altered alignment of the lining walls is shown by chain-dotted lines; between the headwall and the tailwall the lining wall is splayed uniformly downstream, so that, by gradually increasing the bed-width of the rapid, and thus reducing the depth and velocity of the flow, the natural tendency of the water to accelerate its motion is counteracted; this acceleration will be further retarded by the two suggested bars upstream of the tailwall which might be raised, the upstream one by, say, 9 inches, and the downstream one by, say, 6 inches above canal bed. Below the tailwall the lining wall is splayed in the reverse direction so as gently to return the water to the normal bed-width of the canal without concentrating its current centrally. These modifications of the design are simple and cheap, and should be effective in regularising the flow down and below the rapid.

(*c*) *Cascade Rapids.*—This type is illustrated in Fig. 128, which seems a good design, because it brings into play a greater amount of internal resistance by the water so as to reduce its onward velocity at the tail. At each cascade wall the water falls into a water cushion, and then passes up a gentle slope to the one downstream. The design is thus similar to that of the water cushions in series shown in Fig. 7, p. 56, but seems inferior to it, as the volume of water in the water cushions is smaller in the former than in the latter, and has thus less retarding effect. In constructed works the virtual slope of the rapid is continuous between the headwall and the tailwall; in Fig. 128 it ends (as also it does in Fig. 127) at the head of the bay upstream of the latter, thus securing a deeper water cushion at the end of the series.

(*d*) *Power Development.*—Rapids offer good sites for the development of power (Art. 225 (*d*)).

227. Escapes—Tail Reservoirs.

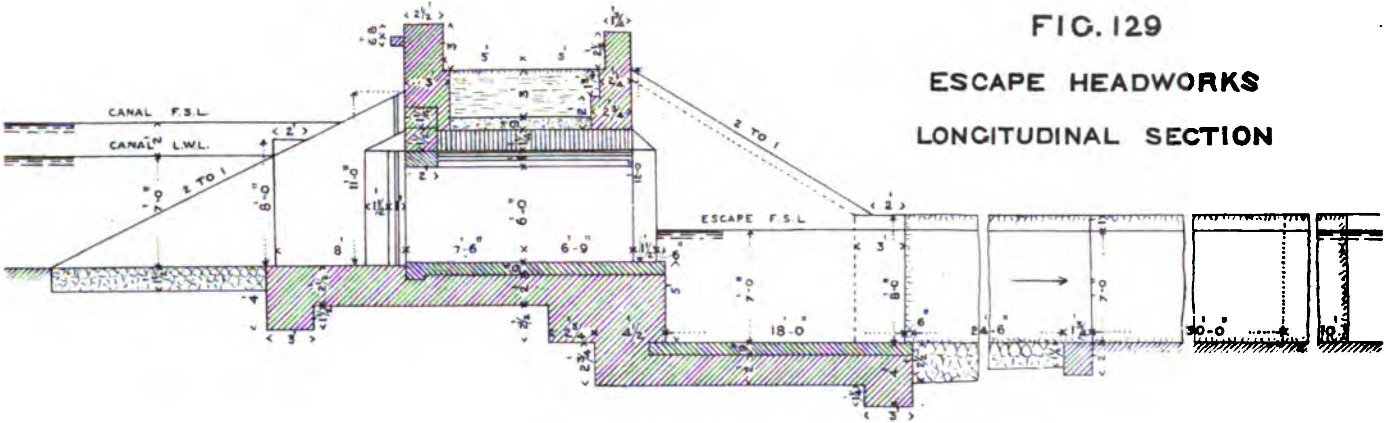
(*a*) *General Remarks.*—Escapes serve two purposes, either for the removal of bed silt from the canal, or as safety valves for discharging surplus water; these purposes may or may not be effected by a single work. They should be located at or near a natural drainage line, so that the escape channel may easily be led into this, and so that its outfall may be kept clear by the scour of that drainage; a long artificial tail channel is even more likely to silt up than the canal itself. To increase their efficiency and to shut off their flood water from passing down the canal they should be placed just upstream of a regulator across the canal, and if such is not required for other purposes it should be specially constructed for these objects. Escapes should, like regulators, have arched vents controlled by sluices.

(*b*) *Silt Escapes.*—The general arrangements for these have been noted in Article 205 (*e*). To pass out the bed silt a high velocity, up to 15 or even 20 feet per second, is necessary; to induce this with the escape sill at canal-bed level there should either be a vertical drop or a short rapid at the head of the escape channel; Fig. 129 illustrates the first type. Opinions vary as to the discharging capacity of an escape which some consider should not exceed greatly one-third of the initial full-supply flow of the canal, whereas others think it should be equal to double that amount. A short-lived but rapid flow has a greater silt-clearing effect than a more prolonged or gentle one, although the total amount discharged may be the same. The quicker rate of discharge, however, necessitates larger and more expensive works. The most efficient economical arrangement will therefore be to have escapes of large discharging capacity near the head of the canal where the silt deposits will be heaviest, and smaller ones lower down. To resist this violent discharge, especially when it takes place suddenly and the escape channel is dry, the downstream pavement should be strong, the sides of the channel pitched for some distance (Art. 225 (*c*)), and scour prevented by tail curtain walls as may be required; in some cases it may be

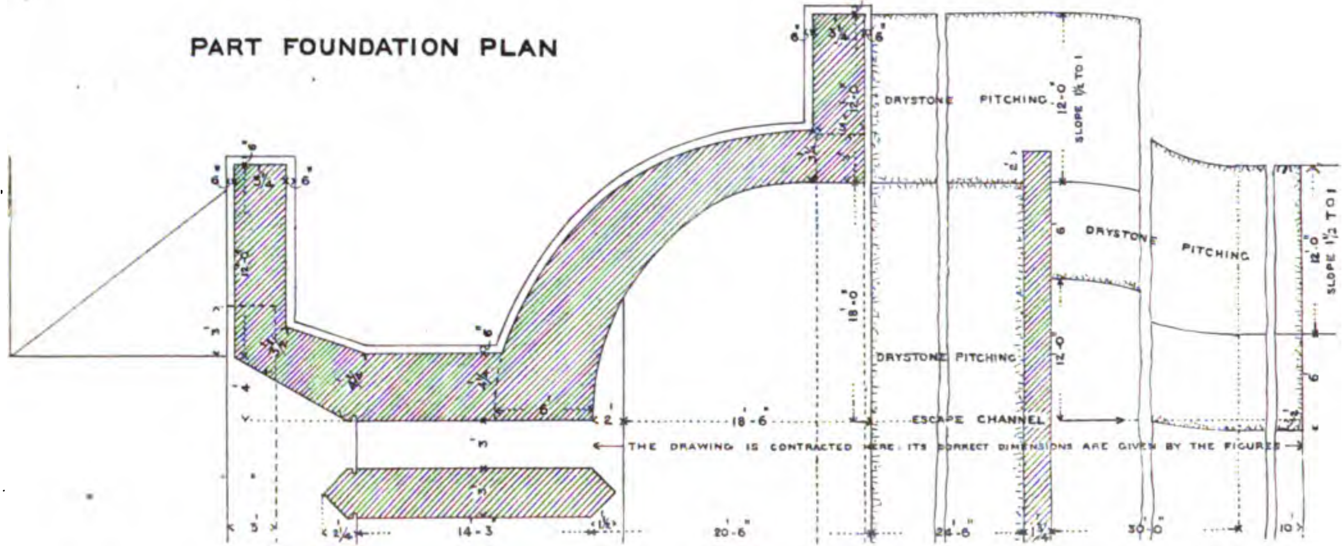
FIG. 129

ESCAPE HEADWORKS

LONGITUDINAL SECTION



PART FOUNDATION PLAN



necessary to construct a tail rapid similar to, but more substantial than, the design shown in Fig. 65, p. 282.

(*c*) *Surplus Escapes.*—These escapes are primarily required to get rid of water in the canal which is in excess of requirements. This may be due—to rainfall causing the irrigators to close their outlets; to flood water entering the canal at level crossings, inlets, or at breaches of the banks; or to the difficulty of regulating discharge down a long canal. Escapes are also useful for laying dry a canal when repairs are necessary or when damage may occur; for the latter reason they should be provided upstream of important embankments or works. As they will chiefly be used to regulate the canal level, they should be distributed at intervals all down its length and that of long branches and distributaries, but they are not required for the two last when those are short. All of them should not be constructed at first, but after actual experience of the working of the canal has been gained; an excessive number of escapes tends to produce carelessness in regulation and to cause waste of water. It is advisable to have an escape upstream of where a main branch takes off from the canal, so that when one of them is closed the surplus discharge may thus be passed off and the supply to the other may not be affected.

A tail escape should be constructed at the end of the canal, so that it may not be necessary to pass surplus water down the tail distributary, where it might be used unauthorisedly or might flood irrigated lands, and so as to allow of a good flow in the canal being maintained down to its end. Where a small perennial flow is available for an inundation canal, a tail escape enables this to be utilised, as then the branch canals which require silt clearance can be closed for that purpose, and the main canal kept open instead of being closed at the head as would otherwise be necessary. Perennial water down the main canal (the head of which rarely requires to be cleared) permits sugar cane and garden and cold weather crops to be grown and rice seedlings to be started early, and it provides water supply for men and animals. The clear flow thus passed down the tail of the main canal picks up and carries off the fine silt deposited there in the inundation season which would otherwise have to be removed by excavation. The tail escape channel can also be used throughout the year as a branch canal for increasing the irrigable area; it should of course have its outfall into a natural drainage line.

(*d*) *Tail Reservoirs.*—For the reasons given in Article 143 it is as desirable, when practicable, to have a tail reservoir on an alluvial canal as on a non-alluvial one. In the former case a site may, however, not be available owing to the flatter country; also the reservoir is more apt to silt up; if this occurs, and it is not feasible to raise the full-supply level, the site may have to be abandoned for storage, and the reclaimed bed of the reservoir utilised for cultivation.

B. CROSS-DRAINAGE WORKS.

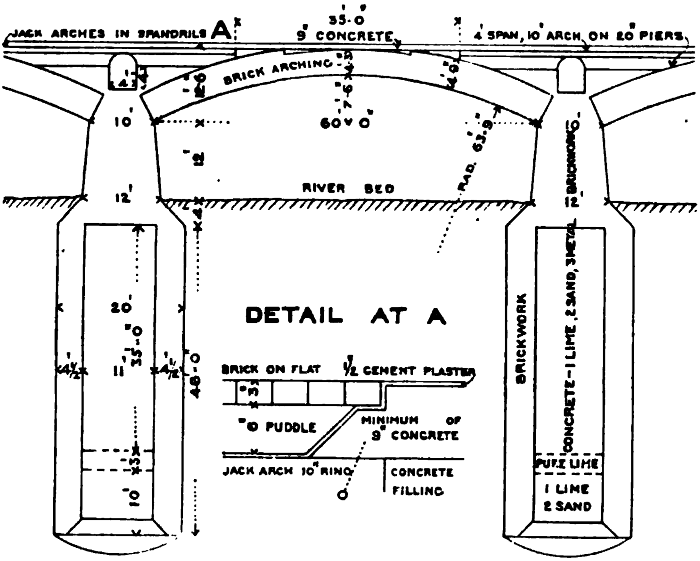
228. Aqueducts.

The design of the superstructure of aqueducts for alluvial canals resembles that of ones for non-alluvial canals (Art. 154 (*b*)), except that on account of the inferior natural foundations spill water is not allowed to pass over the downstream parapet nor is that pierced with silt-scouring vents. Particular care is necessary to ensure water-tightness, as ordinary brickwork is porous; the bed is therefore formed of concrete at the crowns

FIG. 130

AQUEDUCT ON SOFT SOIL

PART LONGITUDINAL SECTION

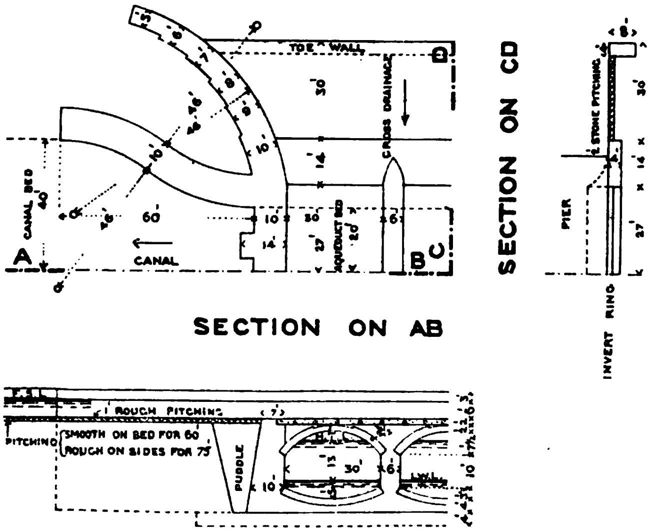


of the arches and brickwork on top of puddle at the haunches (Fig. 130).

A high velocity up to 8 or 10 feet per second is allowed so as to reduce the area of the canal waterway and the cost of the structure. The bed-width of the canal has to be gradually diminished on the upstream side to the aqueduct and gradually increased on the downstream side from that until the normal width is again attained. A rule given for the length of the tapered section is that it should be, for silty, 25 times, and for clear water 5 times, the difference between the ordinary and reduced bed-widths. This tapered section should have smooth pitching on the bed and sides of the canal so that eddies may not be formed, as these would cause scour and erosion, and for the same reason the pitching should extend for, say, one-fifth of the tapered length beyond it on each side; in some works the downstream side pitching is laid rough so as to reduce the excess velocity of flow.

FIG. 131

AQUEDUCT ON HARD SOIL



It is in the foundations that the alluvial aqueduct differs most from the non-alluvial one; on account of the inferiority of the natural soils at the former the cost of its substructure is generally very much greater than that of the latter. For fine sands the foundations usually consist of deep wells which give support chiefly by the skin friction on them; for harder soils the spans have inverts built at their bases, and the structure is carried on a masonry platform with aprons and drop walls as shown in Fig. 131. The extent of protection from scour downstream depends upon the nature of the channel of the cross-drainage, and has to be dealt with accordingly; in inferior soils the bed and sides of that channel may have to be pitched for some distance.

Some of the aqueducts on the important Northern India canals are very large structures, and as great areas of irrigation depend upon them, no expense has been spared to make them secure. Where the few failures have occurred, the fault was due to the under-estimation of abnormal floods; these rise proportionately higher in alluvial than they do in non-alluvial country (end of Art. 222).

229. Superpassages, Siphons, and Siphon Aqueducts.

(*a*) *Superpassages.*—Superpassages for non-alluvial canals have been described in Article 157; for alluvial canals they similarly serve the object of carrying the canal under a flood drainage having its bed at about the same level. The type shown in Fig. 73, p. 303, has, however, not been adopted for the former; probably the objection to it would be that it maintains, for some distance downstream of the work, the high velocity, averaging some 8 feet a second, which is necessary to prevent silt depositing in the superpassage. A more general type is like that of Fig. 74, p. 306 (with the positions of the canal and cross-drainage reversed), as the vertical well downstream checks at the tail of the work the increased velocity passing through it, and a great length of downstream pitching is then usually not necessary. A principal difference is that as generally the drainage will be dry, and the canal in flow, there will be a considerable amount of bursting pressure on the superpassage arch, which will have to be resisted by loading that by masonry or concrete, so that the thickness of the roof may be about four-tenths of the head upstream of the work. There is, of course, no embankment in the waterway of the drainage, which extends unobstructed from parapet to parapet wall. If the canal carries much silt, the type with sloping approaches should be adopted and sufficient protection of the canal bed and sides by pitching and curtain walls should be provided both upstream and downstream.

(*b*) *Siphons.*—A siphon for a non-alluvial canal has been defined in Article 158 as a work leading a canal under a cross-drainage considerably below its general level. For a larger alluvial canal so great a dip is not likely, and a siphon for it might be described as a work in which the canal is carried under a cross-drainage in a structure which is either wholly or partially metallic. In this type sufficient resistance to bursting pressure is obtained by having a thin tube capable of offering tensile resistance instead of a thick masonry vent, depending for its safety on a heavy masonry loading of its crown, and necessitating deeper foundations which will be difficult and expensive to construct in water-charged soil. One form of partially metallic tube depends for its safety on iron straps binding the crown to the invert, so that the weight of the substructure may be made to assist in resisting the bursting effect on the superstructure. If, however, the straps corrode, they will no longer be effective, and to replace them will be difficult ; to avoid corrosion the straps might be grouted with cement or bitumen. Another form of partially metallic structure consists of an inner iron tube acting as a lining to a concrete outer tube ; corrosion will similarly destroy the efficiency of the lining, but might be dealt with by forming the inner tube of iron segments bolted together, each of which could separately be replaced when necessary ; it is believed such a tube has not been constructed. A third form would be a tube made of reinforced concrete ; it would seem advisable to place the reinforcement nearer to the inner surface than theory demands, so that if it corroded it could be more easily replaced.

The wholly metallic tube would be of thick cast iron, and might preferably be built up of detachable and replaceable segments. It would be surrounded externally by a thin shell of concrete, not to increase its strength, but its power of resisting corrosion.

(*c*) *Siphon Aqueducts.*—A siphon aqueduct has, in Article 159, been stated to be a work in which a cross-drainage is carried under a canal, having about the same bed level. Designs for alluvial canals may be similar to Fig. 74, p. 306, illustrating types for non-alluvial canals ; the one with vertical well approaches is best suited for comparatively clear discharges and light soils, as the high velocity through the work is not maintained much beyond it; the one with sloped approaches is most adapted to drainages carrying heavy *débris*, etc., and for firm soils, as the floods will sweep through it with high velocity for some distance. In both cases protection against scour and erosion must be given, as may be necessary, by means of pitching the bed and banks and by drop-curtain walls.

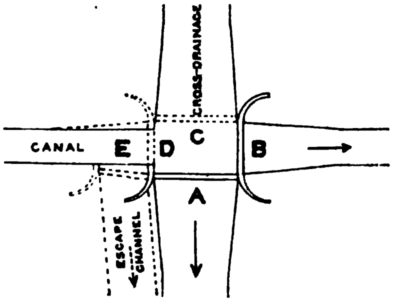
(*d*) *General Remarks*.—These three types of works are generally expensive to construct, owing to the depth of the substructure and to difficult foundations (which are likely to be in water-charged soil), and they are liable to be prejudicially affected by silt deposit; they are thus inferior to aqueducts. On the other hand, they are superior to level crossings, as they do not admit flood water and silt into the canal. It is generally better to pass a heavily silt-charged flow above a light-charged one. Thus when a canal carries much silt a siphon aqueduct would be preferable; where the cross-drainage is liable to bring down boulders and timber a superpassage would be advisable. The extensive blocking by silt of the under waterway might cause a breach of the canal. Much also depends upon the relative levels of the two channels, and, as a rule, the naturally lower one should be passed under the higher one.

230. Level Crossings and Inlets.

(*a*) *Level Crossings*.—A level crossing is a work which enables a cross-drainage to be passed across a canal at its bed level, and is constructed when the beds of the two are practically at the same level; it is best adapted to the case where the cross-drainage has only short-lived and shallow floods at considerable intervals, as during flood-flow much manipulation of the sluices may be required; the floods should also not carry much heavy silt, boulders, etc. The general arrangement is sketched in Fig. 132.

FIG. 132

LEVEL CROSSING GEN^{L} PLAN

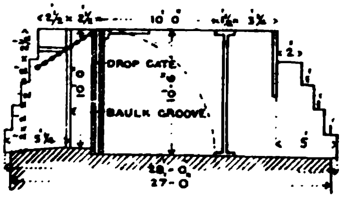


A is the escape wall, the vents of which are opened when the cross-drainage is flowing, and are closed when it is not. B is the canal regulator, which is closed when the drainage is crossing the canal, and opened when it is no longer in flow. In early examples there was a second escape wall, C, parallel to A on the opposite canal bank, the object of which was to confine the canal between the two when the cross-drainage was dry and to prevent the former heading up in the bed of the latter ; this was found not to be of much use, and the arrangement has not been adopted in later works. A second canal regulator, D, on the upstream side of crossing has not been built, presumably on account of the expense involved. It would have the good effect of preventing heavy silt from being deposited in the upper part of the canal and blocking its waterway until it was scoured out through the escape wall vents ; such scouring might take time to effect, although the deposit might not extend far up the canal, as the flow of that is opposed to the passage of the silt-laden current. It would also prevent flood water from entering the canal, and might thus save the expense of long and high-flood embankments, but, as the flow of the canal would be blocked by it, a canal escape, E, would also be necessary upstream.

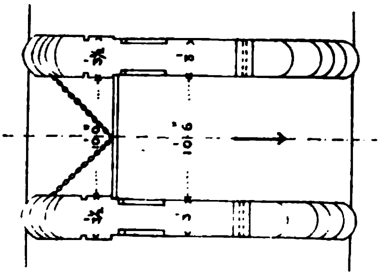
FIG. 133

ESCAPE WALL VENT

LONGITUDINAL SECTION



PLAN



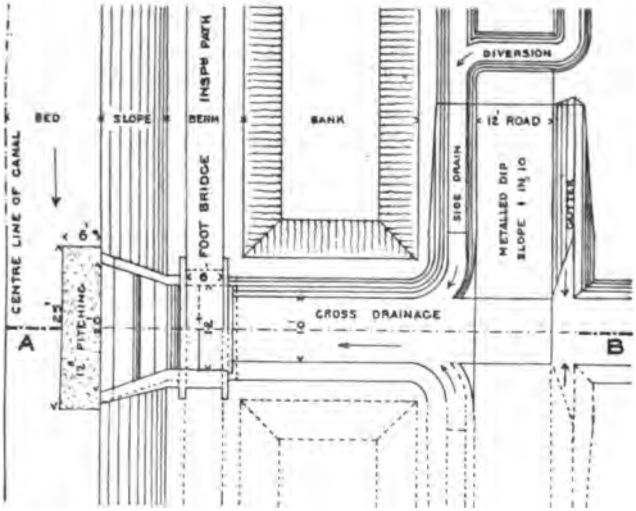
Both the regulator and escape walls have floors at canal-bed level on which piers are erected. The sluiceways of the former are closed by sluices so as to shut out flood water, and the whole work is of the ordinary regulator pattern. The vents of the latter extend only up to canal full-supply level, and are closed by drop gates hinged at their bottom, which, when raised, are maintained upright against the pressure of the canal water by chains, which can quickly be released by manipulating catches when the vents have to be opened, and then the gates fall flat on their sills (Fig. 133). To aid in closing the gates the water pressure is taken off them by dropping planks or baulks into grooves upstream, and then the gates are hauled up by a movable windlass.

It is not necessary that the whole of the escape wall should be pierced by vents, as when the ground levels permit of some rise of flood level, only the central portion need be thus treated, and on each side may be an overfall flank wall raised to canal full-supply level, providing over its crest additional flood waterway to the escape. Protection against scour should be given to the escape tail channel as may be required by pitching of the bed and banks and by building curtain walls across the channel.

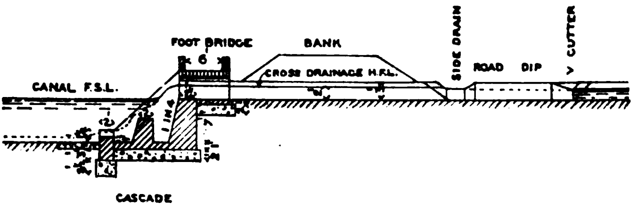
FIG. 134

INLET

PLAN



SECTION ON AB



The objections to level crossings are that they introduce silt into the canal and necessitate the employment, during the flood season, of special gangs to work them at any time when necessary; if this is not properly done serious damage may occur; they are thus inferior to all other types of cross-drainage works. On the other hand, they are much cheaper than those works, and when constructed across streams with a small long-lived and clear flow can admit that into the canal and utilise it for irrigation.

(*b*) *Inlets.*—The object of small inlets on non-alluvial canals has been stated in Article 161 (*b*), and they have been illustrated in Figs. 78 and 79, p. 310. Similar small works can be constructed on alluvial canals also. When the cross-drainage thus admitted into the canal is larger, the inlet would have to be made more substantial (Fig. 134), so as to pass the discharge as a cascade into the canal without damaging it. If the inlet can be constructed at a small depression that can be made to serve as a settling pond or silt trap, it may eventually have to be cleared, and then the excavated silt can be used for strengthening the canal banks. An inlet differs from a level crossing in that it admits water into and does not pass it through the canal.

CHAPTER XIX.

DISTRIBUTION.

231. General Remarks.

(*a*) *Preliminary.*—In Chapter I. the different forms of canal irrigation were described—flow (Art. 5), lift (Art. 6), flood (Art. 7), inundation (Art. 8), and sub-irrigation (Art. 10); also certain systems of irrigation—the "block" (Art. 26 (*e*)), and the "thal" (Art. 26 (*f*)). In Northern India the village lands are treated as the unit, and in other countries the different estates may similarly be regarded. In this chapter will be considered the distribution system under flow irrigation from the main canal to the irrigated lands, where the water may be spread over the ground in small plots, or by means of small watercourse laterals (Art. 24 (*a*)). That system consists of (Art. 2 (x, xi, xii))—

Distributaries, or branch canals;
Minors, or sub-branch canals (or better distributaries);
Watercourses or field channels;

of which the first two should be constructed, maintained and controlled by the administration, while the last-named are usually in the hands of the irrigators. The names first given are those by which the parts are known in India; it seems unfortunate that there the term "distributaries" is applied to canals which do not themselves distribute water to the fields, but lead it to those which do. The alternative names more clearly indicate the functions of the different parts of the irrigation system.

As in the distribution system occurs most of the loss of water in transit (Art. 19), it is necessary to reduce that to the minimum by well aligned, sectioned, and graded channels maintained in good order. Although the engineer's administrative authority extends only down to the outlets at the heads of the watercourses, his influence should be exercised over the irrigators, as it is in their channels and by their defective methods of irrigation that much waste of water may take place. It is therefore desirable that he should align and supervise the excavation of the watercourses, or, better still, construct them at the expense of the irrigators, and should see that they are properly maintained, clear of weeds and silt and free from irregularities, and are worked in the most economic way.

(*b*) *Evolution of Distribution System.*—The importance of a proper system of distribution cannot be overstated, for by it the finished product of the entire irrigation scheme—water (Art. 23 (*a*))—is delivered to the fields, where it is to be made use of for cultivation. The history of irrigation in India shows that this was not recognised at first, as more attention was then paid to the construction of the large works for the supply of water than to the humbler ones necessary for its distribution. Frequently the former were constructed much in advance of the latter, which procedure might be likened to the establishment of a factory and its driving power without provision for the machinery whereby alone that power could be utilised. Thereafter comparatively small sums were gradually spent on the development of the distribution system, so that the large capital expenditure on the main works was prevented from earning sufficient revenue, and thus interest charges mounted up. The proper arrangement is to have a large part of the distribution system constructed by the time the supply works are ready, and to proceed with the extension and development of that system as rapidly as the demand for water necessitates them.

It will not suffice that the distribution should simply be carried out; it must proceed, not in a haphazard way, but in accordance with the best interests of the whole irrigation system on a pre-arranged and well-thought-out plan. In Northern India the old watercourses belonging to individual proprietors were at first continued in use, and the construction of others encouraged by the grant of advances, which were sometimes misapplied and often utilised wrongly with little benefit. This led to perpetual quarrels between the irrigators themselves, and also with the proprietors of lands passed through by the channels. Moreover, the numerous outlets led to great waste of water, while many from the main canal and its branches endangered the safety of the channels and prevented proper control of supply.

The next step taken was to reduce the number of outlets and long watercourses from the canals by providing more minors at Government expense, so as to lead water closer to the villages in proper channels, whence the irrigators could take off their watercourses, and advice was given to them as to the best method of excavating these field channels. The minors were, however, often badly aligned, and sometimes across drainage lines, with only their own object in view, and not as part of a large system to secure the best general advantage, and many of the watercourses were long and irregular. The outlets frequently were built to a fixed size and located in pairs, one on each side of the minor, and not proportioned to the areas irrigable by them.

The final stage was to develop the system of minors, so that they delivered water close to each village, were in accordance with a general scheme of distribution, and were properly aligned with respect to the configuration of the country. Further advice was given to the irrigators in regard to their field channels, and in some cases these were constructed by Government at their expense, which is the best arrangement. The outlets were located and varied in discharging capacity according to proper irrigation requirements; the tendency is to reduce their number and increase their size.

Every stage in this development, and especially the final one, has been attended by increased revenue, extension of irrigation, and benefit to the irrigators.

(*c*) *Evolution of Distribution Methods.*—Not only must the distribution channels be properly constructed, they must also be worked on a well-devised system, if the best result is to be attained, and the least waste is to be incurred. Here again evolution has taken place from crude to perfected methods. During the earliest stage, with numerous proprietary outlets leading from the main canal and its branches, control was not easy. The next stage arrived when such outlets were closed and water was taken only from Government outlets, located at intervals on the minors, each of which was controlled in rotation by the staff. The great number of these outlets, and the considerable length over which they extended, rendered it difficult to arrange for proper rotation (Art. 23 (*b*)), and gave the lower-paid staff undesirable opportunity of blackmailing the irrigators. The final stage was further to reduce the number of the outlets, and to proportion the size and full-supply discharge of each to the irrigable area commanded by it, to run the feeding channel at, or nearly at, its full-supply discharge at intervals, and for periods according to a time-table of rotation fixed by the superior staff, and then to allow all outlets from the channel to be opened at the same time by the irrigators without interference. This change was one of the greatest improvements ever made in canal administration, as it placed control in impartial hands, diminished supervision, lessened wastage, and freed the irrigators from oppression. It also had the advantage of practically dispensing with the necessity for shutters to the outlets at the heads of watercourses, as their discharge is really regulated by the control of the head of the supply channel. When for any reason a particular watercourse has to be kept closed, this can be done by stop planks or earth.

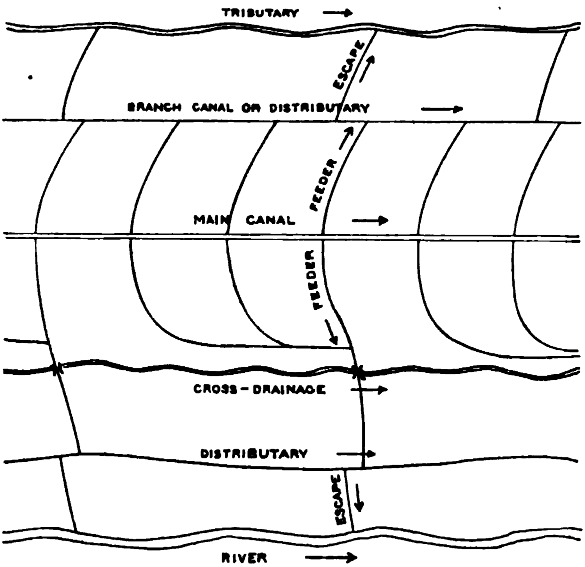
(*d*) *Proper System of Distribution.*—Each village or large estate should have water brought as close as possible to it by channels constructed, maintained, and controlled by the administration. The alignment, construction, and maintenance of the distributary system should be as carefully attended to as for the main canal. The water should be conveyed in the system by the shortest route and in the largest volume practicable, in efficient channels and at levels ensuring rapid irrigation. The sections of the system should be under complete control by the superior staff, but the irrigators should, under that control, be saved from all harassment. The earlier the distribution works are completed and developed, the sooner will the whole irrigation scheme produce good revenue, and the country receive proper benefit ; on this development a considerable expenditure is justifiable, and should prove highly remunerative. The further the administration ensures that development, so as to relieve the irrigators of capital expenditure, which often they cannot afford, the more is it entitled to raise the rates for water supply and in proportion to its own increased expenditure.

232. Alignment of Distribution Channels.

(*a*) *Parallel and Ridge Distributaries.*—When direct irrigation from the main canal was abandoned, the first arrangement was to construct distributaries roughly parallel to that canal (Fig. 135), so as to have only a few outlets from the former, or from the head of feed channels to the latter, and to take out the greater number from the distributaries. At the head of the system where the main canal had not reached the watershed, and even sometimes lower down, the parallel distributaries had perforce to cross the drainage lines of the country, and everywhere to interfere with the drainage of the land upstream of them, all of which entailed extra expenditure on cross-drainage works. Moreover, as the irrigation sections were not independent of each other, it was difficult to arrange proper control of supply by the feed channels, and as the distributaries with progressively diminishing discharge, and therefore continually increasing gradients, gradually diverged from the main canal, it was not always easy to return excess supply from the former to the latter. Lastly, the course of the water from the canal to the fields was increased by the circuitous nature of the alignment which led to slower irrigation, greater loss in transit, and increased expenditure

FIG. 135

PARALLEL DISTRIBUTARIES



on maintenance. For these reasons the construction of parallel distributaries is not now favoured; it is best adapted to a narrow irrigation tract, so as to obviate the necessity for numerous outlets from the main canal.

Ridge distributaries, as their name implies, are led along the ridges crossed or commanded by the main canal. The necessity for cross-drainage works on them thus disappears, the course of the water is made as short as possible, and each tract is served independently of others (Fig. 136, p. 526).

(*b*) *Rules for Alignment.*—The general considerations which have to be taken into account for proper alignment have been mentioned in Article 113 (*a*) and (*b*). The drainage lines should be surveyed and the country to be traversed should be contoured. As far as practicable, these lines should not be crossed, and the channels should be kept on the ridges; where this is not possible, they should be at right angles to the contours; if the alignment leaves the watershed, so much command is lost. Deep cuttings and high embankments should be avoided, and the channels excavated in straight lines and short curves, on the most direct course available. Each watershed should have a channel capable of irrigating its whole command, i.e. down to the drainage lines on each side of it, and each channel should do its own work without assistance from others. The more, within reasonable limits, the system of distribution is subdivided, the easier will it be to regulate supply. Correct and incorrect alignments are shown in Fig. 136, and described on pp. 524–528.

233. Design of Distribution Channels.

(*a*) *General Remarks.*—The larger the distributary the more economical is it. A channel with the same depth and longitudinal and side slopes as those of two channels with half its bed-width will for ordinary sizes discharge nearly as much as they will if the side slopes are 1 to 1, and somewhat more if those slopes are ½ to 1. Compared with the two small channels combined, the single one will have a greater velocity, thus enabling it to deliver the supply more rapidly and to carry on silt more effectually; its wetted perimeter, and thus the loss by absorption, will be less; and its length being only half, the amount of supervision and cost of maintenance will be greatly reduced. At the same time the more the system of distribution is subdivided within reasonable limits, the easier will it be to regulate supply. The arrangement to secure the best results is therefore to have large distributaries and numerous minors of fair but not too small size.

Except in rare cases there should not be any outlets or irrigation direct from the distributaries, and regulation should be applied only at the head of the minors. The distribution system should be designed in respect of discharge and grading from the tail upstream, both in regard to the whole scheme and to its principal subdivisions (Art. 19 (*c*)).

(*b*) *Velocity.*—Taking V_0 as the critical velocity—non-silting and non-scouring (Art. 203 (*c*))—at the head of the system, the main canal and its distributaries and minors should have a velocity equal to V_0 or slightly exceeding it, but never one less than it, or silting will occur. After the first 4 or 5 miles of a head minor, if in that length there has been a draw-off by outlets reducing the silt content of the water, V_0 may be gradually lessened down to $0·75\ V_0$ at the tail. The effect of this will be to cause the deposit of fine mud in the lower lengths, which will staunch them. For the same reason minors taking off from the downstream part of distributaries can start with a reduced velocity, and there may similarly be a reduction of velocity in the lower parts of the distributaries themselves.

(*c*) *Grading.*—The grading of the different parts of the distribution system should be varied in accordance with the velocities which are desirable for them. Thus in Bengal, for minors, slopes of 1·6 feet a mile are given for about the first mile, and the fall is reduced down to 0·8 or even 0·56 foot a mile in the lower parts. The advantages thereby secured are the waterproofing by fine silt of those parts, the water surface is made more parallel to the slope of the country, and high embankments are avoided.

In grading the parts of the distribution system the height of surface flow should be such as will give good command to the channels taking off from them. This entails the design of the distribution from the tail upstream, the neglect of which gives trouble in working supplies. The beds of minors should be kept as near as practicable to the surface of the ground, so as to give command by flow to the marginal fields and obviate the demand for raising the level of the water by stop dams across the channels.

In the case of parallel distributaries there should be a surface fall of at least a foot from the feeder (Fig. 135) into the distributary, so as to avoid the heading up of the former when the supply is low. Similarly, there should be a surface fall of not less than 6 inches from the distributary to each minor.

In non-alluvial systems, where the water is clear and the soil firm and water-tight, the grading is arranged so as to increase the velocity slightly in small channels in order to provide against the greater retardation of flow consequent on defects of maintenance, which may be considerable on account of their small size. This increase of slope is in addition to that necessary to maintain in them the initial velocity at the head of the system because of the small hydraulic mean radius of the tail channel (Art. 116 (*a*)).

(*d*) *Section.*—The proportion of the average depth of minors to their width should be from one-fifth to one-seventh in the case of small channels, and be smaller for large ones. The average depth being taken as two-thirds the true full-supply depth, the latter will thus be from about one-third to one-fifth the width (see Art. 203 (*d*)). Shallow and wide channels have the advantages that they save in the capital cost and maintenance of earthwork and masonry owing to the lessened height of the banks, and also that in them the variation in level of the water due to fluctuations of supply is less. In deep channels, to provide for the greater fluctuation in level, the command at full-supply has to be increased, and this entails an increase in the height and cost of the works. The full-supply depth of minors should seldom exceed 4 feet.

Changes of bed-width should take place below the sites at which water is drawn off, and should usually be by 6 inches for small channels and by feet for large ones.

Changes of depth may also similarly be effected, but usually by much smaller amounts. If these take place in an open length of the channel, they will cause a sudden fall in the water surface, and thereby increased velocity, unless the longitudinal slope of the bed is adjusted to produce them gradually without such a fall (Art. 120). The best site at which to make such a change is just below a vertical fall.

(*e*) *Discharge.*—The discharge of each part of the distribution system should be calculated as for the main canal (Art. 19 (*c*)), with respect to the area irrigable thereby, the duty allowed, and the time during which the section will be in flow, which as a rule should be half the whole time. Where the sections have intermittent flow, each while in operation should be run with from 0·9 to 1·1 of its true full-supply discharge, and during the closure intervals should be dry.

Although the section of the channel may have been excavated with side slopes of 1 to 1, these will eventually silt up to ½ to 1 (end of Art. 117), which latter rate of inclination should therefore be taken into account in calculating its discharge. In Northern India for that calculation Kutter's coefficient is often taken as 0·020 for main canals and distributaries, but as 0·0225 ordinarily for them and always for smaller channels.

In India the maximum discharge is required during the monsoon, and the sections of the channels should be calculated to give it; these will provide amply for the smaller discharges necessary for the rest of the year.

(*f*) *Full-Supply Level.*—An excessive height of the full-supply level above ground surface increases the cost of the banks, and adds to the danger of their being breached. Some extra height beyond calculated requirements is, however, necessary so that the supplying channel may be able to force water over the silt obstruction which is likely to occur at the head of the supplied channel owing to the change in direction of flow which there takes place. This extra height will also be useful if modules for measuring supply are introduced hereafter, as these consume head (Art. 45 (*a*)). For these reasons the practical full-supply level in main channels is kept from 1·5 to 2·0 feet, and in minors from 1·0 to 1·5 feet above ground level. The maximum full-supply level should have really good command, while low full-supply level (which may vary according to the season from one-half to two-thirds of the first named) should have fair command; the latter determines the level of the bed, and thus the height of the former and of the bank.

(*g*) *Banks and Silting Berms.*—In the Punjab the "free-board," or height of the top of the bank above full-supply level, is made not greater than 2·0 feet *plus* the allowance for settlement in the case of large channels; for small ones, not greater than 1·5 feet; and for watercourses, about 6 inches. It is there considered better, when necessary, to widen the top of the bank rather than to add to its height. The nature of the soil, of course, influences the decision, and if that is likely to crack when dry, a greater height is desirable to prevent fissures from descending below full-supply level.

To prevent breaches from occurring, where the full-supply level is high above the ground surface, the banks should be set back so as to allow silting berms to be formed (Arts. 123 and 206). The amount of set-back should be in proportion to the anticipated danger; as a general rule that amount should be such that a line joining the top inner, or canal side, edge of the final berm with the bottom of the outer, or land side, toe of the canal bank will be at an inclination of at least 1 in 6. Where it is not desirable to have borrow pits outside the canal banks, the set-back should be increased to permit the pits to be excavated in the inside berm, and not deeper than 4 feet. The set-back on each side may vary from 2 feet for small watercourses to as much as 20 or 30 feet in extreme cases on main canals.

(*h*) *Masonry Works.*—On properly aligned ridge distribution channels cross-drainage works are not necessary, and masonry works for them will therefore be confined to silt escapes (Art. 205 (*e*)) and falls (Art. 225) or rapids (Art. 226) in connection with the grading of their beds. If the alignment is not on the ridge and cross-drainage is met, it will have to be passed across the channels by works similar to those constructed for the main canal in design, but naturally smaller in size. For the actual distribution of supply outlets (Art. 224) have to be built; they should as a rule be located on minors, and not on main channels, except in rare cases where this will give the water the shortest course, and their number should be reduced to the minimum, so that all on each minor may be in full flow at the same time. The size of the vent of the outlet should be in proportion to the area irrigable, the duty allowed, and the time during which the minor will be in flow between closures.

Masonry outlets are unneccessary for the laterals from watercourses; these can be closed by earth or small sheet iron shutters nailed to a bar of wood and curved and sharpened at the bottom, so that they can be forced into the head of the lateral in order to block it.

234. Remodelling Distribution.

(*a*) *General Remarks.*—Some old systems have such defective distribution that it is necessary to remodel them in order to make them more efficient. The most drastic course is to alter them completely in accordance with modern ideas, but this is not always possible on account of vested interests, the most important of which is that the irrigated areas have been established, and do not always allow of their being served economically by an entirely novel, although better, system. In such cases compromise is necessary, and the remodelling has to be confined to getting a higher duty from the supply, and removing as many defects as practicable. The different arrangements for remodelling are noted below.

(*b*) *Re-alignment.*—Frequently the original distribution channels lead direct to low-lying land near the villages, which themselves were located there on account of the greater fertility of the soil. To re-align the channels on ridge lines would, of course, make their physical command higher but as the existing irrigation has to be served, and it may not be practicable to increase it elsewhere, such a new course, being less direct, might often lead to loss of command at the irrigable area itself. Often the old channels in low-lying land are more water-tight than would be new ones carried along the ridges, where the soil may be more porous. These advantages of the existing system should be taken into account when considering the desirability of remodelling it. It may be noticed that the discharge of low-lying field channels can sometimes be fraudulently made greater by deepening them at the head so as to increase the initial draw-off. The remedy is to maintain the first few feet of the head at the fixed gradient by constructing a small permanent masonry bar or curtain wall across the channel downstream of the length thus to be regulated.

The way in which a complete re-alignment should be carried out is shown in Fig. 136, where the old system consists of "parallel" distributaries occasionally crossing drainage lines and themselves supplied at intervals by feed channels from the main canal, so that the different sections are more or less dependent on each other. The crossing of drainage lines, and particularly the blocking of them by canal embankments, introduces such serious difficulties that wherever possible it should be obviated by a partial remodelment of the alignment where the original one is thus defective, even if a complete alteration is found impracticable. The new system is made up of "ridge" distributaries, which do not interfere with the drainage of the country, as they are led along the ridges, and are also independent of each other; these supply their own minor channels, which similarly are led on ridges.

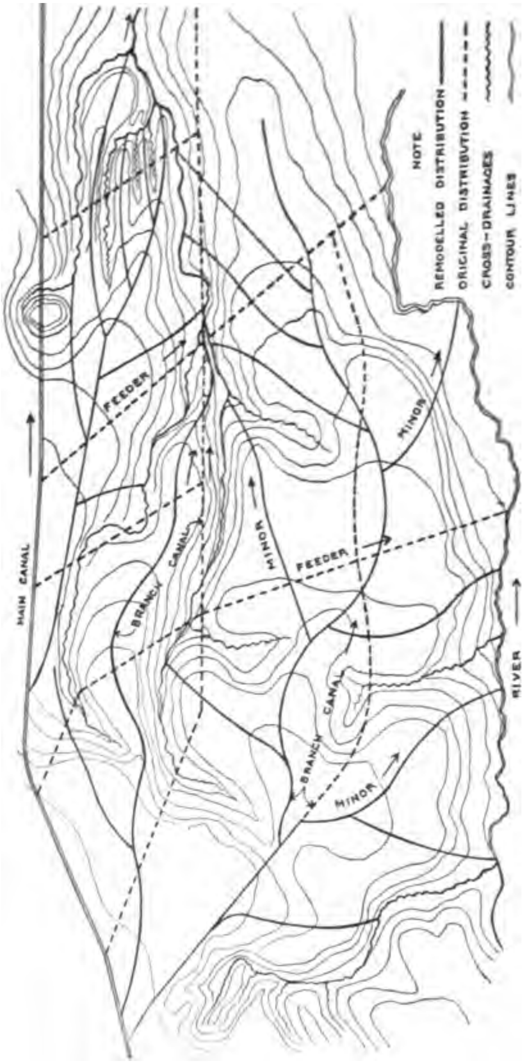


FIG. 136
REMODELLING DISTRIBUTION

In the remodelment it may be possible to utilise some of the old channels.

It will be noticed that the remodelled channels as a whole will probably be more circuitous than the original more direct ones, but the former should be cheaper in capital cost than the latter, as their earthworks will have smaller sections (since they conform more closely to the natural surface), and also because cross-drainage works will be saved; in addition, the former channels should be cheaper to maintain than the latter. The remodelment should also lessen loss in transit, for, although the main channels may be lengthened, they will bring the supply nearer to the irrigable lands, and thus reduce the lengths of the field watercourses in which the bulk of the loss takes place (Art. 19 (*a*)).

(*c*) *Re-grading and Re-sectioning.*—Even when the old alignment is maintained, it is often practicable to improve the grading and sections of the channels so as to make them non-silting. Where there are masonry works across the channels which it is impossible to alter greatly without considerable expense, it will be necessary to take their sills, after any slight change feasible, as the fixed points and to adjust the channel levels between them. Where the original grade was too steep, falls or rapids can be introduced so as to flatten it as may be wanted. When it was too flat, it may be possible to improve it by raising the weir at the head.

In regard to sectioning, the main improvement will consist in increasing the discharging capacity of the channels to enable them to give the supply required to allow the different parts of the system being worked in rotation. The sections of the channels should be improved with respect to the proper proportion of bed-width to full-supply depth, so as to make them non-silting. Minor improvements can also then be effected so as to secure as regular an alignment as is practicable, and particularly those that will lead to an improved gradient and shorter course.

(*d*) *Discharge.*—Each section of the system should have its capacity increased so that it may supply all the outlets served by it at one time in order that proper rotation of discharge may take place, and each set of outlets may be regulated simultaneously by the sluice at its head. The larger channels supplying these sections should be increased in discharging capacity, so as to allow of this rotation.

(*e*) *Amalgamation of Outlets and Watercourses.*—The greatest defect of old irrigation systems is the number of outlets, many of temporary construction, that supply long and irreg ula watercourses, some of which run close to each other for a considerable distance, and have high spoil banks between, thus interfering with silt clearances (Art. 231 (*b*)). The disadvantages arising from this state of affairs are:

(i) Great waste of water due to leakage at the outlets, and much absorption in the watercourses;
(ii) Disputes among the shareholders of the water, and also with the proprietors of lands through which the watercourses pass;
(iii) Serious danger to the main channels, as each outlet is a source of weakness, for it may lead to a breach of the channel bank;
(iv) Impossibility of proper control of the supply leading to theft of water.

The remedy consists in amalgamating the watercourses, and controlling their supply by a much lessened number of permanent outlets constructed to a proper design (Art. 224). Where such outlets have perforce to be built on main channels with considerable depth of supply, their cost is naturally heavy, so that some engineers prefer to substitute new minors for the old watercourses; others, however, think simple amalgamation of a few watercourses together is better, presumably because it interferes less with the existing system of irrigation, and also because the administration cannot attend to numerous small minors. Such amalgamation should be taken up on each main channel consecutively, and the rotation rules enforced thereon before proceeding similarly with another main channel. Regular distribution of supply to all the irrigators under the amalgamation will thus be secured, a sufficient but not excessive supply will be given, and greatly reduced waste of water will result from the shortened length of the combined watercourses, and the more rapid irrigation of the fields; all this will popularise the system of remodelment, and thus diminish opposition to its extension.

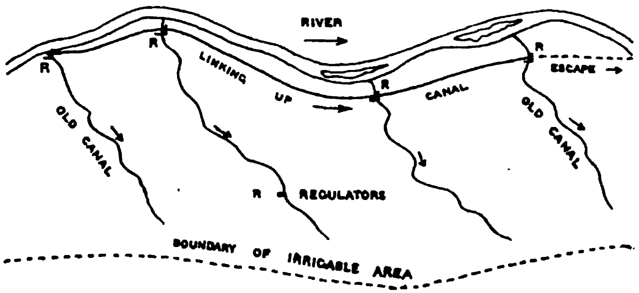
235. Linking up Inundation Canals.

In Article 8 (*b*) were described the defects on inundation irrigation, and how they may be reduced by linking up together a series of canals, so that these may be supplied from a head which is not liable to be injured or left by the river

(Fig. 137). The supply channel from the new head thus virtually becomes a main canal, and the separate old canals the distributaries taking off from it at regulators. This amalgamation secures the following advantages:

FIG. 137

LINKING UP CANALS



(i) *Increased Security.*—As the new head will be selected with a view to securing permanence of the river conditions, it is likely to be superior to the heads of the old ones, which may originally have been wrongly chosen, or may have deteriorated through subsequent changes of the river.

(ii) *Raising the Water Level.*—As the old canals will receive supply from a point of the river higher than their former heads, and the fall of the new feeder will be less than that of the river, *plus* that of those heads, the water level in them will be raised. This raising may be sufficient to allow irrigation to take place by flow instead of by lift, and, anyhow, will reduce the amount of lift.

(iii) *Lessened Silting.*—The silt admitted into one large canal with its head at a favourable site will be less than the total amount which enters several small ones with worse heads. Moreover, owing to the higher level of the former where it crosses the latter, it may be possible with it to excavate a silt escape channel (Art. 205 (*e*)) back to the river, which will still further reduce the silt passed on. Even when there is no reduction in the total amount of silt derived from the river, the depth of deposit in the longer lengths of the new system will be less than in the old canals, especially the ones downstream, and thus supply in them will not be so much reduced by silting.

(iv) *Utilisation of Silt.*—By the better velocity of the supply canal, owing to its larger discharge and improved section and grading, the finer fertilising silt will be delivered to the supplied canals at lower points than originally, and, by the substitution of flow for lift irrigation, most of it can be carried on to the fields instead of being chiefly deposited in those canals.

(v) *Facilities for Rotation.*—By the combined system it will be practicable, when necessary during bad seasons, to supply the old canals in rotation, which will utilise the water better by preventing a good deal of waste by absorption.

(vi) *Improved Irrigation.*—Where flow irrigation can be substituted for lift irrigation, the water will be passed more rapidly over the land, thus spreading it more evenly over that, as there will be less absorption in the higher parts of the fields (Art. 24 (*d*)). Further, by such substitution the expense of irrigation will be greatly reduced.

The proposed great Rohri canal project in Sind will in effect be an example on a very large scale of the benefit of linking up old inundation canals, as the contemplated new main canal will supply many of the existing canals, now having a fluctuating flow affected by the vagaries of the Indus, with perennial water at a high, and practically constant full-supply level, and will obviate the dangers attendant on their present direct heads from the river.

CHAPTER XX.

LAW, FINANCE, AND ADMINISTRATION.

A. LAW.

236. General Remarks.

(*a*) *Evolution of Irrigation Law.*—In new countries irrigation is usually started by individual farmers for the development of their own particular estates, and without consideration of the requirements of others. This process continues until the irrigating community increases to such an extent that the different interests conflict with each other, and it becomes necessary to devise systems of law and administration to regularise matters, to secure justice to all, and to obtain the maximum amount of benefit to the country from the limited and probably fluctuating amount of water which is available. Unfortunately, the early evolution of irrigation noted above introduces considerable difficulties, as frequently rights are assumed which constitute a bar to progress, and there is an entire absence of that scientific method which is an absolute essential to proper development. The main characteristics of water, from the point of view of irrigation, have been described in Article 25 (*a*), and State control of it has there been advocated as the best and fairest form of management by impartial, competent, and sympathetic administrators. At first among the original irrigators there will naturally be strong opposition to any limitation of the claims to which they have grown accustomed, but this will gradually be borne down when the evils of irrigation chaos are realised, and the advantages of a just law and firm administration are recognised. Until this is accomplished, irrigation will always present difficulties; to lessen these the legislature should keep the final end in view, and should devise its measures in a steadily progressive and not retrograde spirit. Fortunately, at the start of irrigation the individual abstractions of water and the works in connection with them are usually small, as then there is seldom either the capital or the knowledge necessary for the construction of large schemes for the utilisation of the flow of large rivers, or for impounding the yield of considerable catchments. A new country intending to develop irrigation should from the beginning vest in the State the control of all large rivers, and the storm waters not arising directly from any private property, if it desires that success in its operations which has attended irrigation in old countries where all waters are held to be national property, which has to be utilised for the best general benefit.

(*b*) *Final Development of Irrigation Law.*—In old countries where irrigation has long been practised, law based on custom has established the principle on which alone proper progress can be effected, and the systems there in force, which are the result of long-continued evolution, are the best guides to new countries. In the East the control of all water has for centuries been invested in the State, but irrigators are secured in their old-established rights, and where they exist in communities are practically allowed themselves to administer all their internal irrigation concerns. In the West the further a State has progressed in irrigation, the greater is its general control centralised, and its claim increased to administer more and more of the water supply as a national asset for the fullest public benefit.

In India there are larger areas under irrigation by modern State and by ancient native works than in any other country in the world. Government there is the owner of all non-private water (that which is not produced on a private estate). In the case of State works it rents water to irrigated lands for short terms, which are renewable, but does not grant it permanently; it constructs and maintains the works and distributes the supply therefrom. In the case of ancient native works Government practically hands over to the irrigating communities the distribution of water in accordance with old custom for the supply of fixed lands entitled to it; these works were probably constructed by the then Government, and the present Government effects improvements and major repairs, and assesses the lands for irrigation benefit received.

237. Water-Rights.

(*a*) *Determination of Supply.*—In irrigated countries under State control the primary administrative duty of the engineer is to distribute water to those entitled to it. In such countries where riparian rights exist it is necessary to determine their extent, and the priority under which they can be exercised. For all irrigated countries the determination of the rights of irrigators has first to be settled definitely, otherwise there is no basis on which distribution of the available supply can be carried out. To enable this to be done it is most desirable to follow the principle of the hydrographic district (Art. **3** (*a*)), so as to make each irrigation system, or tract, independent of others by being separated from them by natural watershed lines. The next step to take is to find out the amount of water available, and that is done by a series of gaugings, which should be as complete as possible, and should consist of observations at each channel below its off-take, and at intervals down the stream, so that the total discharge due to run-off and seepage, less loss in transit, may be determined. The longer these observations are continued, the more accurately will the average flow and its seasonal variation be ascertained. The increase of " duty " due to better irrigation arrangements should be taken into account in apportioning supply to the irrigators. All this technical examination is beyond the capacity of the irrigators themselves to conduct.

(*b*) *Shares of Water—Priority of Right.*—Where the State distributes supply to individual irrigators, it is the duty of the engineer to limit the area irrigated in accordance with the water supply available, and particularly in seasons of small discharge to effect every economy practicable, including as a final measure the rotation of supply (Art. 23 (*b*)), which is in accordance with the ancient custom of distribution by shares, not fixed quantities (Art. 25 (*a*)). On riparian streams effect is given to the contrary principle of " priority," which entitles irrigators to their supply in the order in which they originally acquired their right to it. Although this principle is correct in that it secures vested interests, it may lead to waste by loss in transit and diminished return by seepage when lower proprietors have the first claim to water, and it is deficient in justice when holders of late rights are thereby totally deprived of water in seasons of scarcity.

It would be fairer to combine as far as practicable both the principles of priority and shares. Similarly, when the State leases large supplies from one source to several corporations, etc., who distribute it to their constituents, the quantity allowed to each during ordinary good seasons should be reducible *pro rata* with the reduced total discharge available in bad seasons. In America it has been found that the law of priority stops progress and permanent irrigation, and in India, under the old native systems, that it similarly retards expansion of cultivation, as the original irrigators prefer to use water extravagantly rather than economise for the benefit of new comers.

In regard to riparian streams the main order of priority is that water is usable for—(1) Domestic, (2) Agricultural, and (3) Other purposes. Domestic purposes include drinking supply to men and animals, and household requirements; these entail only a small consumption of water. Agricultural purposes are practically confined to irrigation, and other purposes to applications for power. When power schemes return water to the stream, they do not usually affect lower irrigators prejudicially. In regard to irrigation, priority is governed by the date from which beneficial use of the water has been made and continued; in doubtful cases the upper proprietor would have the first claim to supply. In advanced countries, where the ownership of water is vested in the State, that grants water-rights by permit, and then fixes their priority; in such cases the right granted is the use of water under fixed conditions, and the State does not surrender its ownership.

(*c*) *Procedure for determining Water-Right.*—As soon as it becomes necessary in the interest of riparian irrigators (those whose lands wholly or partly border a stream) to settle their water-rights, their claims should be inquired into from the irrigation point of view to establish the facts, and appeals from such decisions should be to the Courts, in order that legal points may be determined. The procedure to be adopted would be somewhat as follows:

The engineer should be prepared with correct hydrographic (gaugings, etc.) and topographic (plans, etc.) record, and should then issue notices to all interested in the settlement to meet him on the ground, so that the inquiry may be properly carried out. Those who do not submit claims should lose their right to water, and those cited to appear who do not attend the inquiry should forfeit their right to appeal (this proviso is to obviate adjudication being blocked). The engineer should report the result of his inquiry, and submit its record to the administrative sanctioning authority, which should pass its order and communicate it to all interested parties; such order should be subject to appeal to the Courts within a prescribed time—that is usually fixed as a year. Pending appeals the order of the sanctioning authority should hold good unless the applicant binds himself by bond to pay damages which may accrue by the suspension of the order. A water-right confirmed by both administrative and legal authority is practically unassailable; as a matter of experience very few appeals are made, as would-be disputers are aware that the facts have been established during the inquiry, and the Court will adjudicate only on legal matters.

(*d*) *Conditions for Water-Rights.*—The principal conditions attached to water-rights are:

(i) The water must be used beneficially, i.e. for irrigation. In Spain, if water is not used for a year and a day, the water-right lapses, and if the supply is then utilised by another, the original proprietor cannot resume it, even although he constructed the works by which it is made available. This provision is devised to ensure that the water is fully and continuously utilised so that the maximum benefit from it is obtained.

(ii) The water must not be wasted; this follows from (i).

(iii) The fixed amount of the water-right must not be exceeded without permit. In order that this condition may be fulfilled, in some States in America each right-holder is required to fix a measuring device at the head of his channel within ten days of receipt of notice to that effect, failing which supply is shut off. The irrigator is held responsible if such gauge or his sluice is tampered with.

(iv) The water-right is attached to a definite area of land, and is in proportion to its extent, but the locality of that area may be altered after permission to change it has been granted by the sanctioning authority, which should follow engineering advice as to this.

(v) The water-right has to be exercised from the fixed point of diversion of the supply to the channel until the alteration of that has similarly been allowed.

(vi) Where new water-rights are granted by permit, they are allowed on condition that they do not interfere with existing rights, and are exercised within a prescribed time limit and continued thereafter. All works required for the diversion of supply have to be sanctioned before water is taken, and for this, again, engineering advice should be followed.

(vii) When riparian rights are exercised under State control, it is found that the best way to ensure compliance with orders is to retain power to refuse supply when orders are disobeyed.

238. Record of Rights.

As riparian irrigation grew up under no correct system, so claims to water were made without right foundation, and did not rest on a scientific hydrographic basis. When a proper system becomes necessary, and is sanctioned, such claims have to be examined and settled so as to secure justice to all—frequently the total of the claims to water is equal to many times the actual supply available. The rejected claims having thus been inquired into and dismissed can be filed, and no further record of them is required, but the accepted claims have to be carefully registered and maintained up to date in order that the documents in connection with the secured rights may be permanently on evidence and available in the event of later dispute. In the case of State-controlled works, where water is leased for short terms, the question of water-rights does not arise, and no record of them is therefore required.

A record of rights is necessary—

(i) To define existing rights (which is the initial step to be taken);
(ii) To supervise the acquirement of new rights;
(iii) To control the distribution of water; and
(iv) To prevent future legal disputes.

For these purposes the record must be prepared and kept up to date by irrigation experts, and be subject to review by the Courts as noted in the last Article. The acquirement of new rights must follow the same system as that adopted for ascertaining old rights. The investigations and records in respect to all rights must keep pace with the applications received. All transfers of irrigable area and of points of diversion of supply must be entered in the record, otherwise it becomes of no use in registering the actual state of affairs in accordance with the most recent sanctions. The whole record must be clear and complete in detail, so that it may be accepted as authoritative by a Court of Law.

239. General Prescriptions for Law.

(*a*) *Main Principles.*—It may be said that the main objects of legislation are to—

Assist and protect right-doers;
Deter and punish wrong-doers.

To attain the first of these it is necessary that a law should be precise, comprehensive, and simple in its arrangement. To gain the second object the penal provisions of a law should be drastic, otherwise they would be inoperative by their feebleness, and would conduce to the suffering of wrong by those who should be protected by the law. At the same time, due latitude should be given to the administrators to meet cases where damage has occurred more through ignorance than wilful wrong-doing.

Failures in irrigation have generally not been due to wrong application of water, but to bad laws and deficient control. There is no form of legislation more difficult than that connected with irrigation. Irrigation on any scale without proper administration is impossible; to secure that administration, centralised State control is necessary. A good law should take into account the physical, social and political circumstances which affect irrigation; where this has not been done, the law has often been a failure. Irrigation works carried out in accordance with physical conditions and administered with proper control under a good law must succeed, if not at first, eventually. A law which was originally designed for a country with a humid climate (where water is looked upon as a nuisance to be got rid of by drainage) is not applicable to a country with an arid climate (where water is regarded as a blessing to be fully utilised). The development of irrigation is greatly affected by the water law under which it is practised, and particularly by the prescriptions fixing the ownership of the waters, beds and banks of streams.

(*b*) *Administration Necessary.*—Irrigation being both an art and a practice (Art. 1) requires to be administered by experts, and not by lawyers; the trained engineer should be entrusted with its management, and the lawyer should be called in only when legal rights are in dispute and have to be settled. American experience shows the necessity that exists for keeping irrigation matters out of the Law Courts, and experience in India and elsewhere how seldom recourse to them is necessary. This is due to the fact that the interests of the administration and of the whole body of irrigators are the same. A great advantage of administration is that it is elastic, and can better meet the varying circumstances, sometimes unforeseen, which occur than can a law rigidly prescribing action and similarly liable to be confronted with novel conditions. A further advantage of administrative regulations is that they can enforce economy in the use of water; the Courts admit that they are unable to decide this on general principles which will meet all the contingencies that may arise. It has to be remembered that irrigators are for the most part simple agriculturists who prefer to deal with a sympathetic administrator who is acquainted with them, understands their requirements from a practical point of view, and can give prompt decisions, which, however, are liable to review by superior administrative authority, all without cost. They are naturally averse from appealing to the law, with its lengthy procedure, and with the only certainty that it will entail expense.

(*c*) *Civil and Common Law.*[1]—There are two main classes of law which affect irrigation—the Civil Law and the Common Law. The Civil Law was established under the Roman Empire, and is one of its most beneficent enactments. By it water is considered to be the common property of all; it is thus vested in the State (Art. 25 (*b*)), and it cannot be made the personal property of private owners. Under this law water is not attached to real properties, nor is it controlled by riparian owners, who cannot get fixed rights thereto; those can be obtained only by permit of the State, or after undisputed beneficial use continued for a long time. The principle of this law gives the State administrative control of streams, and by preventing litigation, affords security to irrigation enterprise.

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[1] *Vide* "Report on Irrigation Legislation and Enterprise," Cape Town Government Printer, 1898, by Wm. Ham Hall, from which remarks below as to the practice, etc., of different Governments are derived. Also, "Irrigation Development, France, Italy, and Spain," State Office Sacremento, 1886, by the same author.

By the Common Law of England water is not held to be the possession of the people, but to be attached (even in the case of public water) to riparian lands, the owners of which can demand compensation when deprived of their supply. Even there administration has been enforced in respect of streams for sanitary regulation, for navigation, and for the protection of riparian owners, but not for that of the population as a whole, which is thus not given its natural right to a necessary element. No water-right is assured until by litigation it has been secured against other applicants for it; its tenure is thus most uncertain, as it is liable to be attacked at any time.

Where the Civil Law prevails, irrigation prospers by the security afforded to all sanctioned enterprise, and the most progressive irrigating countries are those which have adopted it. Where the Common Law obtains, irrigation languishes, as settled rights are essential for it. As the Common Law is relaxed and the provisions of the Civil Law are adopted, so does irrigation develop.

240. Laws of Different Countries.

(*a*) *America.*—(i) The United States. The different irrigating States in America have various irrigation laws, the effect of which illustrate the remarks made at the end of the last Article. The Federal Government itself holds its lands within the several States simply as a proprietor, and not as a sovereign authority, nor does it control those States. Irrigation is not understood by the American people as a whole, for six-sevenths of them live in the humid Eastern States, where it is not required; the arid Western States, which depend much upon irrigation, however, comprise three-fifths of the whole area.

(ii) California is an English Common Law State. The original irrigation law was made by lawyers, and established many rights, but no regulation, was vague in its prescriptions, had only local application, and did not provide for executive administration; it is an example to be avoided. The Californian irrigation law of 1887 is also a failure, and has been amended or supplemented by fifteen or sixteen subsequent Acts, but is still unsuccessful in meeting the conditions necessary for proper irrigation. Other Common Law States have similarly failed to secure irrigation development.

(iii) Colorado in its Constitution declared that unappropriated streams were the property of the public, subject to future appropriation, provided for the right to divert water therefrom for beneficial use, and laid down that priority of application governed the exercise of such right. Legislation was, however, slow, has been piecemeal, and in some respects conflicting; administration was at first not secured, and the acquisition of unlicensed rights was permitted. Subsequently, all claims to water had to be established after proper inquiry and a record of rights was made. A system of State control has been legalised, but is not sufficiently strong nor comprehensive.

(iv) Utah is an arid State, with rich soil and water convenient for utilisation. The original settlers did not understand irrigation, but were entirely controlled by their leaders, the elders of the Mormon Church, who laid out settlements so as to avoid conflicts over water-rights, and when these appeared likely as the population increased, prevented them by general regulations. From the first riparian rights were not recognised, and gradually a system was evolved similar to those of Civil Law countries, and particularly to that of Spain, and this has many good features.

(v) Wyoming has developed the best system for irrigation in America. The original Constitution in respect to water was on the right lines, but has been improved by being made more definite, and by declaring all water to be the property of the State. The revised Constitution provides for the administrative management and regulation of streams, water, and irrigation by a Board of Control, with State officials under it. Riparian rights are not recognised, and water can be appropriated only by permits, the grant of which is subject to administrative and legal control; water-right and irrigation matters are definitely settled.

(b) *Australia.*—Victoria is the only Colony which has made good progress in irrigation, chiefly by the development of trusts; some of the first of these have, however, been great failures, owing to the want of proper engineering examination, indifferent cultivation and bad financial arrangements. Irrigation Acts were passed in 1885, 1886, 1890, 1900, and 1904. A water-supply investigation has been in progress since about 1883, and since 1896 an engineering expert has been employed to devise a system for the carrying out of irrigation schemes.

(*c*) *France.*—In mediæval times the law was feudal, but had a groundwork of Civil Law; in modern times the law has been developed in the direction of the latter, to the benefit of irrigation. Navigable streams are of the public domain, and are exclusively controlled by Government. Non-navigable streams were formerly claimed by the riparian owners; they are now held by the State for general public benefit, but riparian owners have a preferrent right to use their water under administrative control and permit. Government can utilise excess water for the irrigation of non-riparian lands; riparian rights have been gradually and steadily curtailed. On navigable streams the Administration decides all questions and grants all permits; on non-navigable streams it regulates the works and the Courts decide water-rights. On both classes the Administration obtains the data required for settling disputes; it does not modify materially or set aside well-defined rights of usage, but aims at just regulations in the interests of all; it withholds rights which are not utilised, and may refuse riparian rights which are against public utility or those which interfere with the domestic use of lower owners. New riparian owners are given permits which entail only more economical use of water by old users, but not such as would deprive them of necessary supply. Each stream has its own special regulations, and under these the distribution is left to the irrigators; appeals to the Courts are allowed, but few of them are made, as it is realised the Courts are likely to support the disinterested Administration.. Right of passage and rights of storage and abutment are enforced for public works, and their acquisition is facilitated for private works. Economy in the use of water is effected by administrative regulations. The enactment of laws to meet all cases necessitates numerous Court rulings, whereas the object in view is to keep questions out of Court, and this has led to a system of administrative management.

(*d*) *Italy*.—In early modern times Italy had feudal law with a basis of Roman Civil Law; the water law has now fortunately gone back almost entirely to the Roman law, which originated in her country. "When[1] Victor Emmanuel consolidated Italy into one country, he decreed at the outset of his reign that the whole of the rivers and torrents of Italy were part of the public domain, and, as such, the property of the Government representing the people. Old irrigation rights of thousands of years' standing stood in the way of such legislation, but the Government of Count Cavour possessed a strong hand. Having decreed the rivers and torrents as public property, the Government in the same bold and decisive manner defined with great accuracy all the indefinite and vague claims of centuries, and then set itself to legislate for future concessions. Modern Italy owes much of its prosperity to this wise and strong legislation."

Practically the riparian owner as such has now no rights in respect to streams. No one may divert public waters or establish mills, etc., except under confirmed ancient rights or administrative permit granted by Government on payment of rent. Drainage and surplus water has to be returned to the stream. The laws in respect of right of way for canals are most complete; they provide for the speedy determination of all questions, and always in the interest of the new work on payment of fair but not excessive compensation for damage done thereby. Provision is not made for Water Courts, as old rights are well established, and Government sees to new rights. There are councils of arbitration of irrigators under large works which settle matters relating to the use and distribution of water; there is the right of appeal from them to the Courts.

(*e*) *Spain*.—There is no feudalism in the water laws of Spain; they are based on the Roman Civil Law and on ancient irrigation customs. The present water code (1879) was devised so as to have one general irrigation law instead of many different local ones and Government decrees. It classifies waters according to their source, thus:

(i) Fallen waters—storm water from rainfall;
(ii) Risen waters—springs and other naturally rising sources;

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[1] "Report on Irrigation in South Africa," by Mr. (now Sir) W. Willcocks, 1901, Transvaal Government Press, Pretoria.

(iii) Flowing waters—normal flow of rivers and streams;
(iv) Standing waters—ponds, lakes, and marshes;
(v) Subterranean waters—underground or caused to rise artificially;
(vi) Drainage waters—the discharge of sewers or drains.

An owner of land is entitled only to the water which falls, rises, rests, or is produced on his land. Flowing water in streams and water which passes into them is public water belonging to the State, which also owns their beds and banks up to ordinary high-flood level, and has a right to use their immediately adjacent lands. There are no private streams, and riparian owners on public streams have no rights except as utilisers of water. They have a preferrent right to acquire the use of public waters of small streams, thus:

First—the properties through which the water flows in order from the head to the tail of the stream;
Second—the properties fronting the stream in similar order.

This right is acquired only if exercised every year for twenty years, and then becomes absolute, but only if the water is utilised for irrigation; if not utilised, the right may be lost. The right to water is thus an acquired and not a natural one. Riparian right is therefore much limited, and cannot be exercised to prevent others from acquiring right to waters.

On rivers not navigable riparian owners have no water privilege beyond that of other land owners; all alike have to apply for administrative permits for water. Permits are, however, granted to owners of riparian lands preferentially to those of back lands, provided the former make prior application. The law does not recognise the appropriation by any one of public waters, i.e. the absolute possession thereof, only the right of user is granted, and water must be profitably utilised, and not wasted, nor not used, nor applied so as to injure other interests. Rights not exercised for a year and a day may lapse, and will be forfeited if others then use the water thus set free; this important regulation ensures that full use is made of the national asset of water. The law provides, entirely by administrative process, for the acquirement of a right of passage, of a right of abutment, and of servitudes on land required for works; the procedure for acquiring the last named is simple, and is the result of centuries of experience.

(*f*) *India.*—There are separate Acts for each of the principal Provinces in which irrigation is extensively practised; they follow each other closely, with due allowance for local circumstances, and have been in force for various periods—in the older Provinces for upwards of forty years—with very little change. Under them a very large area of irrigation—now over 20 million acres—under many classes of works and under many varieties of physical conditions is successfully irrigated with practically no recourse to the Law Courts. All water is vested in Government; all matters are properly defined; the appointed administrative officers are empowered to carry out their specified duties; all arrangements for the construction of works and the distribution of supply are laid down; rules for settling compensation by summary decisions or formal adjudications are prescribed; and procedure as to revenue matters, penalties for breaches of the law and appeals is settled. In some Acts measures of administration are expressly withdrawn from the purview of the Law Courts.

241. Objects to be secured by an Irrigation Law.

From the above review and from general experience the objects to be secured by an Irrigation Law may thus be summarised:

- (i) Conformity with physical, social, and political conditions;
- (ii) Clear and precise definitions and prescriptions of all general matters;
- (iii) Elasticity to meet varying conditions in minor matters;
- (iv) Sufficiently deterrent penalties for all wilful breaches of the law;
- (v) The vesting in the State of all water, or, where this cannot be done, for the best utilisation in the public interest of water hitherto not utilised, or which is not likely to be utilised by private development;
- (vi) The greatest beneficial use of the existing water supply;
- (vii) The administrative control of the distribution and beneficial use of water;

(viii) The revenue control of all public schemes;

(ix) The engineering control of all works which may endanger public safety;

(x) The grant by simple administrative procedure of all powers and rights required for the construction of works, e.g. acquisition of land and materials, settlement of compensation for damage, etc., and rights of passage, abutment, and servitude;

(xi) The confirmation of all existing water-rights and customs after due inquiry;

(xii) The protection of existing rights by appeal to the Courts within prescribed periods;

(xiii) The grant, when necessary, of the normal flow of small streams to riparian owners;

(xiv) The grant by administrative permit of future water-rights;

(xv) The legal attachment of water to defined irrigated areas from fixed points of diversion both entitled to alteration when sanctioned;

(xvi) The evolution of irrigation development by proper scientific methods;

(xvii) The economical administration of local affairs by elected bodies under proper supervision and control;

(xviii) The prompt settlement by administrative measures of all engineering matters without recourse to the Courts;

(xix) The avoidance of expensive litigation, as far as practicable, by local inquiry and arbitration;

(xx) The simplification of legal procedure when litigation is unavoidable.

B. FINANCE.

242. General Remarks.

In respect to financial arrangements irrigation works may be classed as—

(i) Small private works belonging to individuals or small communities;

(ii) Large private works belonging or having their water leased to companies, corporations, or trusts;

(iii) State works which may be small but usually are large

The State is interested in all three classes—in the first two indirectly, and in the third directly—since all, when successful, increase the assets of the whole community, and, conversely, when unsuccessful, decrease these. In regard to the first, financial arrangements should be very simple, and will probably take the form of loans to the agriculturists, repayable with interest in a term of years, for the maintenance, improvement, or extension of their works.

In respect to the second, the arrangements are more complicated ; instances of the assistance granted by certain States are given in the next Article.

Large private works are most adapted to advanced countries, the inhabitants of which are accustomed to independent action and to speculative commercial enterprise. In them the State will benefit by giving due scope to such initiative, and for works thus constructed by restricting its direct action to general supervision and control in order to ensure that the schemes are technically and financially sound, and that the rights of individual irrigators are not exploited by unscrupulous corporations.

The development of the country will be best assured by the third class, especially in eastern lands, where irrigation takes place on the largest scale, and by comparatively backward communities unaccustomed to large commercial enterprises and generally dependent on the State for advancement, and accustomed to deal with its officials. As in the case of small private works, the assistance of the State in respect to its small indigenous works will generally consist in their maintenance, improvement, or extension, not, however, by loans, but by its own agency. By maintenance, the State will secure its existing revenue, and by improvements and extensions, will somewhat increase that.

243. Large Private Works.

(*a*) *General Remarks.*—Under this head are classed together works which either belong or have their water leased to companies, corporations, or trusts. When water from State works is thus leased, the State maintains the works, as in the case of those wholly managed by its agency, but does not concern itself with the distribution of water except to impose general regulations for its supply to individual irrigators under the systems. Examples of the way in which different States aid in development by private agency are given below.

(*b*) *America.*—It has been held that development should be ensured by the following arrangements:

(i) Encouragement of irrigation enterprise by making it possible to acquire title to the irrigable lands commanded by the works;
(ii) Government or State drawing up or passing of the schemes, and supervising their construction;
(iii) Government or State limitation of the sale price of lands and water under the works thus constructed;
(iv) Government or State guarantee of water-right free from litigation, just as it practically guarantees similar title to land.

The Arid Land Cession Act enacted in 1896 should assist the development of irrigation fn the Western States of America.

(*c*) *Australia.*—A Royal Commission appointed in Victoria in 1896 recommended that in dealing with Trusts—

(i) The Department should closely supervise expenditure by Trusts, and for this reason should be furnished with estimates and contracts for works;
(ii) A proper examination of applications for loans should be instituted;
(iii) The Irrigation Trusts should be made entirely responsible for their acts;
(iv) Loans should not be granted in excess of 50 per cent. of the rateable value.

These restrictions were suggested as there had been failures of Trust operations owing to their neglect of the warnings of experts, excessive expenditure being incurred without financial control, loans not being repaid and speculation taking place.

(*d*) *France.*—Government aids irrigation development in the following ways, by—

(i) Remission of tax assessments for many years on increased valuations due to irrigation;
(ii) Loans on favourable terms to associations and companies undertaking irrigation works;

(iii) Advances to such associations and companies on the cost of their works, and acquisition of their works on payment at the expiration of long-term concessions;
(iv) Guarantees of interest on capital invested in works;
(v) Construction of main irrigation works at State expense and transfer of them to associations for management;
(vi) Similar construction of works for districts which afterwards repay their cost to the State, and manage them under administrative regulations;
(vii) Construction of and management by the State as public works of irrigation schemes which are too large for private enterprise.

Organisations taking Government loans bind themselves to carry out the works according to approved plans and Government supervision, and to manage them under pre-arranged administrative regulations. Other assistance is given by inviting competition in and granting premiums for the best irrigation practice; by collecting and publishing irrigation statistics and other useful data; and by sending experts to examine the irrigation projects and methods of other countries.

(*e*) *Italy.*—The assistance afforded by Government to private irrigation enterprise resembles that granted in France. Zealous care is taken to protect the rights of irrigators and landowners, as experience has shown this to be necessary, for, otherwise, the strong would injure the weak, and the nation as a whole would suffer.

(*f*) *Spain.*—Irrigation is encouraged by Government by—

(i) Exemption from customs duties on machinery and implements employed on irrigation works;
(ii) Exemption, partial or total, of taxation on irrigation development;
(iii) Grant of power to collect irrigation rates;
(iv) Direct subsidies of money to the cost of schemes;
(v) Direct subsidies by gift of lands or sale thereof at nominal prices.

Subsidies have been to the extent of 50 per cent. of the estimated cost of the works.

(*g*) *India.*—Commercial projects are non-existent; two large ones were started in the early years after India came under the Crown, but proved failures, and were taken over by Government. State assistance to irrigation is given by the construction, maintenance, and management of public systems which are generally large.

244. State Works.

(*a*) *General Remarks.*—In endeavouring to develop irrigation, the State, so far as its financial conditions permit, should adopt a well-considered, defined, sustained, and steadily progressive policy suited to the country and keeping pace with, but not much in advance of, its requirements. When the revenue is good, considerable progress can be made; when it is poor, construction will have to be reduced, but then is the time to make investigations and draw up schemes for execution when funds allow, and thus the engineering staff can be employed continuously without fluctuation in its strength. In order to secure continuity it is advisable to lay down a five years' programme, to carry it out or modify it as circumstances necessitate, and to prolong it in advance. It should be a standing rule that commenced works should have the first claim on funds to enable them to be completed early, in order that previous expenditure may not remain idle, and so that they may be brought into operation and may earn revenue, and create benefit as soon as possible. To obtain the confidence of all, the schemes most likely to be successful (Art. 56 (xxiii)) should first be undertaken unless others are wanted to meet special requirements, such as protection against famine. The State should, however, not limit its operations entirely by financial considerations, as private enterprise is compelled to do, but should be guided in its stewardship, so as to advance the country as a whole, including its backward districts, and in doing this can pool results, for irrigation is beneficial even if only it stops retrogression. In all cases due consideration should be paid to the matters noted in Chapter IV in respect to careful preparation of schemes, sound construction, and economical arrangements.

(*b*) *Loan Account Works.*—To ensure steady and sufficiently rapid progress, the State, any more than an ordinary capitalist, should not depend entirely upon its revenue resources, but should have recourse to loans when it has to construct very large and costly schemes likely to produce favourable financial and economic results. The loans should be on general account, and portions of them devoted as necessary to the completion of individual works. For the sake of simplicity in classification it seems desirable that the whole expenditure on a loan account work should be financed exclusively from loans, and not partly from them and partly from other funds, although such amalgamation of funds is sometimes adopted. Where there is a surplus available from such other funds, it might also be exclusively devoted to financing other similar works, and thus classification of the schemes under finance heads would be clear and defined.

(*c*) *Capital and Revenue Accounts.*—After a project has been completed in accordance with its construction estimate, that estimate should be closed, but the Capital Account should remain open so that sanctions from it may be given to supplementary estimates for works subsequently found necessary, as will generally be the case. Such works should ordinarily be entirely new constructions, and not of the nature of maintenance; when, however, an existing work has to be renewed or replaced, the cost of the renewal or replacement should be charged to the Capital Account, and that of the original structure should be written back from the Capital to the Revenue Account. Thus at any time the total of the booked expenditure on Capital Account will represent the initial cost of all the works of the scheme then in existence.

The Revenue Account on its credit side will show all the receipts of the work from sales of water, etc., and on its debit side all charges for maintenance which should be carefully made, and none of them written off to the Capital Account. The gross receipts of the work, less maintenance charges, will be the profit from it, and this reckoned on the total Capital Account will be the percentage return of the capital expenditure incurred on the whole scheme.

(*d*) *Direct and Indirect Charges.*—In India the debits to the Capital Account are of two main classes:

(i) Direct charges—Cost of works, establishment and tools and plant, of which the two last are percentages on practically the whole cost of the first;

(ii) Indirect charges—Capitalisation of the abatement of land revenue on areas occupied by the works, leave and pension allowances, and interest on expenditure during construction.

The result is that the engineering cost is increased by a large percentage, sometimes up to 50 per cent., and the scheme has to give a return on the grand total of the direct and indirect charges. It is, however, credited only with direct receipts, and does not receive any allowance for indirect receipts. The latter will include many items, such as increased earnings on railways owned by Government, greater spending power by the people, more immunity from scarcity, lessened crime and the cost of its prevention, etc. It is impossible to assess the amounts of these, but it is certain they aggregate to a considerable sum by which Government eventually benefits. It would therefore seem fair to debit a State engineering scheme only with the actual cost of the works and of the establishment, and tools and plant employed on their construction, and to consider that the other charges now made are offsetted by the indirect benefits received from the project. This would clearly establish one advantage of State works over private works; the latter do not derive such indirect profits, which accrue only to the State. It is true the State acquires them from private works without expenditure of its own, but this naturally diminishes the attractiveness of schemes to private enterprise. The inclusion of indirect charges in the capital account may prevent the undertaking of a scheme desirable in itself, but which is unremunerative as thus estimated.

(*e*) *Water Rates and Revenue Forecast.*—Matters in connection with water rates have been discussed in Article 26. On new works it is advisable at intervals of, say, five years to revise the rates fixed, in order that they may start initially at low figures, so as to encourage irrigation, and may gradually be varied to amounts which can justly be imposed as conditions alter. Before a scheme is sanctioned, a forecast should be made of its probable revenue during, say, the first twenty years after its completion; this should take into account the original and altered water rates and the probable effect of their variation on the extent of the irrigated area. In this respect State works have an advantage over private ones, as Government can wait longer for adequate returns from its expenditure, being greatly interested in promoting the welfare of its cultivators as far as this is in consonance with general public policy.

(*f*) *Budget Rules.*—Funds allotted to one main budget head should not be utilised for works scheduled under another such head without the sanction of the authority passing the budget, but works under the same head can have funds transferred from one to another by administrative sanction; the transfers should be properly accounted for, and the amount originally sanctioned for a work should not be exceeded without proper authority.

There should be a lump sum provision in the budget for unforeseen and urgent works, such as those which are necessary for the immediate repair of damage, which will chiefly occur in the flood season; later in the year the unexpended balance can be transferred to other works. Other lump sum provisions are required for surveys, hydrographic work, tools and plant, etc., so as to meet demands, the exact amounts of which cannot be foreseen when the budget is prepared.

To avoid lapses of grant, sanctions to works provided for in the budget should be granted as soon as possible. To facilitate this there should always be a balance of sanctioned schemes drawn up ready for execution.

Works should not be stopped because of excesses on estimates, as this would involve further excess in re-starting them, and cause loss of revenue by the consequent delay in completion. Excesses can be met from the total budget provision, as it is unlikely that the whole of that will be exceeded in a financial year. The officers in charge of construction should be held responsible for excesses of over 5 per cent. and for reporting in time when they are likely to occur, so as to enable, if possible, reductions to be made in incomplete parts of the works. Engineers in charge of districts should be authorised to make purchases and to fix rates for labour, materials and work for works in progress, and should be made responsible for any excesses that may thus be incurred.

The Revenue Account of a work should receive credit for all revenue collected from it, including book credits from other departments for water utilised by them, etc.

(*g*) *The Financial Year.*—Works should be continued at the start of a financial year without interruption, even if the budget is not then sanctioned, as funds for them should eventually be provided. It would be a great improvement if for all public works in tropical countries the financial year commenced at the close of the flood season, as that automatically causes construction to slow down during its continuance, and, moreover, affects many trade interests similarly.

(*h*) *State Assistance.*—On Government works the chief assistance to irrigation is their construction, the cost of which is wholly defrayed by the State. Other assistance would be given to cultivators by temporary loans, improving communications, encouraging co-operative associations of irrigators for obtaining farming supplies and marketing produce, and by establishing experimental stations and giving agricultural advice as described in Article 27. The collection of hydrographic statistics (Art. 4 (*c*)) will help the country generally.

C. *ADMINISTRATION.*

245. General Remarks.

(*a*) *Control.*—Irrigation on any scale without administration is an impossibility, and therefore the irrigation law of a country should strengthen as much as practicable the hands of those who will have to administer irrigation. The legislature should define what is good public policy, and the administrative officers should see that the principles laid down are enforced, and should not themselves initiate them without sanction. Irrigation being a branch of engineering, its practical administrators should be engineers; their administrative acts should be under superior departmental control, and not under legal control; the latter should be confined to the settlement of disputes as to water and other rights, and to the award of penalties for breaches of the law. When, however, suits are brought against the staff in the exercise of their administrative functions, the State should hold itself responsible for defending them. As irrigators are as a class simple agriculturists, it is the duty of the staff to treat all questions sympathetically, and to practise leniency in administration in order to educate the cultivators to recognise the advantage of control exercised in the general interest. The credit of the staff and the prosperity of the irrigators are thus bound up together.

(*b*) *The Staff.*—The primary administrative duty of the irrigation engineer is to distribute water fairly and impartially, and especially in seasons of deficient supply; for this water-rights must be well defined by the law, seeing they are essential as a basis for proper distribution, and the engineer must have a thorough technical knowledge of the hydrographic conditions of his charge. He must also be expert in designing, constructing, and maintaining irrigation schemes. Irrigation is a specialised branch of engineering, and differs from ordinary professional employment, chiefly in the following particulars:

(i) It is concerned with areas as well as with lines of communication;
(ii) It deals with the cultivating class, and involves much revenue management;
(iii) It has intimate relations with several other Government departments;
(iv) The magnitude and cost of large irrigation works, combined with their general moderate financial return, usually render them unattractive to commercial enterprise, and therefore such works, especially in the East, are generally carried out by a Government staff.

The hydrographic investigations which form the scientific basis of irrigation work are preferably conducted by a Government staff. Continuity of work, systematised and impartial observations, and a comprehensive and easily accessible record are thus best secured.

In a new semi-tropical country the professional staff has another important duty, and that is the education of the political administrators in regard to the necessity for irrigation to secure proper agricultural development, for frequently such administrators will be ignorant in respect to irrigation, and thus not able by themselves to appreciate its benefits.

For these reasons a trained irrigation department is most desirable for a country in which irrigation is or is to be extensively practised, and a State is well advised to recruit carefully and maintain properly its own staff, as it will be difficult to depend upon outside enlistment.

246. Administration in Different Countries.

(a) *America.*—The various States have different irrigation staffs, but as a general arrangement an establishment consists of water masters, division engineers, a State Engineer, and a Board of Control. The water master attends to the regulation of water on the system in his charge, he works under the division engineer, whose professional chief is the State Engineer. The Board of Control regulates all matters; its officials are all appointed by the State, and consist of Commissioners, each representing a territorial division, with the State Engineer as President. The duties of the engineers are to supervise the design, construction and maintenance of all reservoirs, and determine what they may store; to inquire into the financial ability and good faith of applicants for carrying out schemes; to investigate possible schemes, make surveys and gaugings, and collect hydrographic data; to examine claims to old and applications for new water-rights. The Board of Control confirms old ones thus established, and grants permits for new ones for which application is made.

(*b*) *Australia.*—In each of the different States, under a Minister, is a Department of Water Supply, which controls irrigation generally, draws up State schemes, examines, passes, and superintends those originated by Trusts, and carries out surveys and hydrographic observations.

(*c*) *France.*—At the head of the administration of irrigation matters is the Minister of Public Works, and with him is the Council of State as the highest Board of Appeals and permissory authority. Under these are the Prefects and Councils of the Departments (territorial divisions) of the Republic, and under them the Mayors and Municipal Councils. The Minister as chief executive officer has the civil Hydraulic Engineering Corps to assist him technically in regard to investigation and planning, and the Public Works Department to carry out the construction and repairs of State works. The Prefects are the chief local authorities in regard to non-technical administration; they grant permits for the smaller streams, after getting technical advice from the engineers, and advise the Minister in respect of permits for larger streams; the Minister or Council also act upon technical advice or information from the engineers.

The Administration does not attempt to modify materially or set aside well-defined rights of usage, but examines claims and aims at just regulations in the interest of all. It prevents unreasonable people from holding rights they do not utilise; it may refuse riparian permits on the ground of public utility, and may decline to allow a work to be constructed which may deprive lower owners of their domestic or needful supply; it gives permits which entail only more economical use of water by old users, but not such as would dispossess them of their needful supply; and by administrative regulations it enforces economy of use.

Irrigation associations of landowners are called Syndicates; they elect their own executive and make their own rules, but all important matters are referred to the whole Syndicate, and everything is subject to State administrative control.

(*d*) *Italy.*—The irrigation administration is similar to that in France, but is more autocratic and more dependent on the central authority. The administration of streams is carried out by officers under that authority; there are not any elected councils to serve as boards of appeal from executive rulings.

Italy has the largest associations of irrigators in the world. These do not build works, nor until recently manage them, but lease water in bulk from large State works and distribute it to irrigators by their own officers under their own rules, subject to Government supervision.

(*e*) *Spain.*—The administration of water is less democratic than that of France, and less autocratic than that of Italy. The officers are the Mayors of communities or municipalities, the provincial Governors and the Minister of Public Works. The Advisory Boards are the Municipal and Provincial Councils and the Council of State. The lower officials have less authority than those in France. Although the general tendency is to liberalise in local administrative matters, the reverse is the case in irrigation ones, i.e. the latter are being taken away from the local authorities and are being centralised in the provincial Governors and Minister. This is very significant, as up till modern times old local systems of water administration were followed; the alteration is due to the fact that modern irrigation schemes are controlled by their councils, which are too powerful to be coped with by mayoral authorities.

The policy is to combine water with the land irrigated thereby, and, even under concessionaire systems, to entrust its management to locally elected bodies, where 20 or more irrigators and 494 or more acres are served; these work under Government control, which ensures compliance with regulations and fair treatment to all. The basis of voting for such bodies is a property qualification, and Government sees that all interests are properly represented.

Communal administration is effected by locally elected

Syndicates (executive) and Juries of Irrigation (judicial), which are independent of each other. The members serve without pay, and they are legally bound to act when elected. From the Syndicates there is appeal to the executive office of the Province, and from the Juries to the provincial Administrative Court, but not to ordinary Law Courts. Each landowner entering an irrigation community binds himself to abide by the decisions of its officers and the Boards of Appeal.

There is an engineering organisation in each Province, the chief of which reports to the Governor, and a State department of engineers, the chief of which reports to the Minister. Of these engineers certain are deputed to hydraulic work, and become the technical advisers of the administrators, while others are the professional experts in charge of the construction and maintenance of irrigation works.

(*f*) *India*.—The country is divided into several Provinces, over each of which is a provincial chief—Governor, Lieutenant-Governor, or Chief Commissioner—and in the larger Provinces these are assisted by local Executive Councils. The Government of India exercises supreme control so as to ensure the needful amount of uniformity in regulations and procedure. The technical work of irrigation is wholly entrusted to the Irrigation Branch of the Public Works Department, and each Province and the Government of India has its engineering secretariat, which works under the head of the Province or a member of the Executive Council. The Secretary to Government is a Chief Engineer; the district staff consists of Superintending (in charge of divisions), Executive (in charge of districts), and Assistant Engineers and subordinates. Judicial administration is carried out by the Magistracy, and is subject to the control of the Courts. Appeals are of the rarest occurrence, as on new systems Government maintains the ownership to water, leases it on short terms, and does not grant it permanently; while under the old native works the water is shared by the irrigators in accordance with custom, which dates from immemorial times.

The Irrigation Department is responsible for the construction, management, and maintenance of all Government schemes, comprising all varieties and sizes of works, of which some are the finest in existence, and these irrigate a total area much in excess of that of any other country. The old native works are generally maintained by the Department; they consist principally of small reservoirs, but there are also small weirs, from both of which channels are led, and these also irrigate a very large area in the aggregate.

The State works are on the whole most remunerative and successful in general improvement, and prove that in the East wise and just State administration is best adapted to ensuring the development of the country by irrigation, and the prosperity and happiness of its agricultural inhabitants, which react so as to assist the advancement of the whole population in wealth and civilisation.

PART II. WATER SUPPLY OF TOWNS.

CHAPTER XXI.

GENERAL MATTERS.

247. Introductory Remarks.

WATER-SUPPLY schemes are required to increase the health (drinking and sewerage), convenience (domestic and public), trade facilities (manufactures), and safety (fire extinction) of the population served by them. Usually, that population will be concentrated in towns for which medium-sized to very large projects will be necessary, but sometimes it will exist in smaller numbers, or in isolated situations for which small works will suffice. In all cases the sufficiency of the quantity of supply made available is the first consideration, for, unless this is assured, supplementary supplies may be resorted to, and if these are not under proper supervision, or are liable to pollution, the health of the whole community may be endangered. Quality of supply, although highly desirable, is of secondary importance, as minor defects in the original condition of the water can be made good by treatment, although at extra expense; unimprovable inferior supplies should of course be rejected. Naturally, the schemes that furnish supplies which are abundant and also good are the best, and every endeavour should be made to secure both requirements. In regard to quantity it has to be remembered that the amount of consumption will probably become greater by the increase of the population and the larger use by individual consumers, which will be made as the utility of the supply is developed. A project should therefore be considerably expansible to meet such enlarged demands, for if it has hereafter to be supplemented by an entirely new scheme, both the capital and maintenance costs are likely to be unduly increased, and the operation of the combined system rendered more difficult than would be the case were the original works themselves sufficient after expansion as found necessary.

Further, the nature of the different constructions must be as reliable as possible, and risks should not be run in order to save expenditure. The supply must also last throughout the longest period of drought probable, and under the worst natural conditions, for any deficiency, even of short duration, would cause much inconvenience, and possibly result in danger to health. This implies that observations as to its variation should be prolonged so that full hydrographic information may be made available for a complete natural cycle, which in temperate climates has been taken as extending for at least thirty-five years. Failing such a record care should be taken to err on the side of safety and to secure a supply by precautions, which for an irrigation work might be considered excessive.

The cost of a water supply scheme is usually borne solely by the population and interests served directly by it. As such cost is generally great, it has, however, been considered in some backward countries that State financial assistance is permissible when without it the expense involved would prevent the construction of a project. The justification for this help there is that an urban community is the centre of the neighbouring area, of which the rural population is benefited by the prosperity and healthiness of the town, and may suffer if the conditions are the reverse. Moreover, the former should set a standard of good sanitation to the latter, and to the country generally. A small town, unable originally to pay for the cost of a complete scheme, may well start with one less comprehensive, but designed so that it can be improved subsequently, as even the initial works will be superior to an unorganised supply, and may lead to increased prosperity, which may render development practicable. Such works might consist of storage or intake, furnishing water for a small rate of consumption, a simple masonry or concrete conduit, or even open channel, aligned suitably for the future supply main, an open service reservoir, and a few distributing mains, with a street service for draw-off.

248. Quantity of Water.

(*a*) *General Remarks.*—The proper determination of this has been stated in the last Article to be of the greatest importance in designing a water-supply scheme. Unfortunately, it is attended by much difficulty, as the variations in use are so considerable, depending as they do upon the characteristics of the inhabitants and the nature of the towns. Not only must present requirements be met, but future ones for a reasonable number of years must also be satisfiable. The unit of supply in statistics is the number of gallons consumed per head per day, and therefore the number of the population and its probable growth have first to be arrived at from census enumerations. The introduction of a water-supply scheme is, however, likely to increase the previous rate of increment of the population, and also its rate of consumption. The effect of such enlarged demands can best be estimated from a consideration of the growth and development of similar towns, for which purpose the similarity taken into account must include all factors on which consumption depends.

The requirements for supply of towns can be divided into the following classes of consumption :

(1) Domestic, (2) Commercial, (3) Public, and (4) Waste;

and the present rate and probable growth of each has to be determined.

The variation in total consumption in gallons per head per day is illustrated by the following general figures of what takes place in different countries :—America, 30–270; Australia, 30–50; England, 15–50, average 25; European continent, 10–50; India (rural), 5–10, (capitals) 25–30.

In addition to the ordinary diurnal variation of rate of consumption there is also a seasonal one; the maximum occurs in summer (when supply is naturally at a minimum), and is about 25 per cent. in excess of the average. Judging from this alone, one would expect the total rate would be highest in tropical countries instead of being the lowest; this is due to the lower civilisation and greater poverty of the inhabitants there. The maximum draw-off thus occurs at a time when most countries are at their driest, and care should therefore be taken in the case of schemes which depend upon natural supplies that they can then be assured of sufficient water. In the case of artificial supplies due to storage the quantity impounded should suffice to tide over the longest period of drought.

(*b*) *Rainfall the Source of Supply.*—The rainfall is the ultimate source of every kind of supply, and in temperate climates it is usual to consider the effect of its total annual amount. "Glaisher's Law" is that the average fall of three consecutive years yielding the least fall may be taken as the average minimum fall. "Hawkesley's Law" is that from the average fall of twenty years one-sixth should be deducted to obtain the average of the three years of minimum fall. These two laws apply to conditions in England, and should agree in their general result. Another rule followed there is that the mean rainfall for the three driest years is 80 per cent. of the general mean. In America it is considered safer for this to adopt 75 per cent., or even less. Taking the mean British rainfall for a long series of years as 1·00,[1] the rainfall for abnormal years is: The wettest year, about 1·50; the driest, 0·67; the average of the driest two consecutive years, 0·75; and the average of the driest three consecutive years, 0·80. To meet the possible deficiency of replenishment, English storage reservoirs in the north are made with a capacity of from 120 to 140 days' supply; those further south with one of from 160 to 180 days', and those in the extreme south with one of from 200 to 250 or more days' supply.

In India and other tropical countries it will not be safe to take the annual rainfall into account, but only that part of it which is likely to produce replenishment (Art. 50 (*a*)) or flow. It will be much better there and elsewhere to rely upon actual gaugings of discharge than to estimate from the rainfall the amount of supply available. Rainfall statistics should be resorted to only when records of discharge are not available (Arts. 48 (*d*) and 51). Storage reservoirs in these countries, unless they are situated in areas certain to produce yield even in the worst years, should generally have a capacity to last for two years without appreciable replenishment during the second one. This implies great loss from evaporation when that occurs; in the first year when the reservoir surface exposed is large, and in the second year when the balance storage is shallow and the water is thus warmer, and will be subject to prolonged and intense evaporative action of unusually dry and hot air. The sufficiency of the capacity in these conditions should be determined in some such way as that described in Art. 50 (*b*).

(*c*) *Domestic Consumption.*—Under this head are included drinking by men and animals, household requirements, baths and closets, and in some cases garden supplies, although the last might better be classed under commercial consumption. Apart from garden irrigation, a highly civilised community should not utilise more than 15 to 20 gallons a head a day for domestic purposes.

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[1] *Vide* Symons' "British Rainfall, 1883," p. 32.

(*d*) *Commercial Consumption.*—In this class fall trades, manufactures, industries, and large establishments where the rate of consumption is high. The quantity required for each should be liberally estimated, and the total thus arrived at divided by the number of the general population to obtain the average additional number of gallons per head per day required for this purpose.

(*e*) *Public Supplies.*—These consist of water for street watering, sewer flushing, public fountains, gardens, and institutions, and for fire extinction. Each use should be separately estimated, and the total similarly divided to obtain the additional rate per head of the population. Fire extinction is the most important, and it has been calculated that for it the *per capita* allowance in gallons a day should be at the rate of $\frac{1000}{\sqrt{x}}$, where x is the number of the population in thousands.

(*f*) *Waste.*—This may be divided into two main classes —unpreventable and controllable. Of the former instances are the loss by evaporation in reservoirs and seepage at sources of underground supply; also the increase of leakage due to the deterioration of the joints of mains in the course of time. Of the latter the principal causes are bad plumbing, leaky taps and fittings, and careless use by consumers; there should be little loss from the mains when new if they are properly laid. To control such waste the general methods adopted are insistence on the provision of specified good house fittings, house-to-house inspection and metering the supply, either of sections of the town reticulation or of individual consumers. Inspection is vexatious, and by itself does not give statistics of the saving effected by it. The metering of sections of the mains will enable the lengths and areas where loss chiefly takes place to be ascertained, thus reducing the extent of remedial measures; it is advisable to adopt such metering in all cases. The metering of supplies to large commercial consumers is also desirable. The metering of ordinary domestic supplies generally leads to a large economy of water (the reduction in certain cases has exceeded 50 per cent., and will usually be not less than 25 per cent. of the whole supply), and is especially necessary where consumption has to be limited. In regard to general regulation meters should be fixed at the source of supply, at the pumping station, and at service reservoirs. For the first and last of these the "Venturi" meter is one of the best, as by it the head lost is small and the measurement is very accurate. In pumping systems a check on varying consumption can be obtained by fixing on the engines recording instruments to register the rate of pumping. The objections raised to installing meters are the considerable expense involved, the possible inaccuracy of the meters, and the risk that after they are fixed the consumers will limit their draw-off to less than is required for proper sanitation. The first objection might be met by metering at first only districts where much waste has been detected, and gradually increasing the meters in less wasteful areas; the second can be provided against by inspection and testing of meters alleged to be faulty; and the third can be obviated by fixing a minimum charge sufficient to cover the cost of adequate supply. The reduction of waste not only effects economy, but improves sanitation, especially in tropical towns where mosquitoes breed freely in damp localities and propagate malaria.

249. Quality of Water.

(*a*) *Desiderata for Water.*—Although the sufficiency of the quantity of water available is the first requirement, that of its quality is of very great importance. The best schemes are those in which the quality is naturally of a high order, and after them come those in which the natural supply has minor defects which can be remedied effectually and cheaply; sources which are inherently bad should, of course, be rejected. The first consideration is that the water should be potable, wholesome, and free from disease germs; other considerations are connected with its use for domestic and manufacturing purposes. Chemically and biologically pure water is not obtainable in Nature, for although the rainfall which alone furnishes potable supplies is distilled, it dissolves and absorbs matters and germs in its passage through the air, and on the surface, and in the subsoil of the ground. All such matters and germs are not deleterious, indeed some are beneficial and improve the originally pure water for use. Examined physically a good water should be free from colour, odour, objectionable taste, deposit, and turbidity; should possess a clear, sparkling appearance; and should have a refreshingly low temperature.

(*b*) *Preliminary Examination.*—The engineer can make the preliminary physical examination of a contemplated source of supply and satisfy himself that the water under investigation has the good physical qualities above mentioned. Thereafter, if it stands such test, he should carefully examine the gathering ground from which it is derived and see if it is free from, or liable to, sanitary contamination, and if the latter is the case, whether it is practicable by engineering arrangements, such as diversion of contamination, to improve the natural conditions. Further than this it is not advisable for him to proceed, as detailed scientific examination is best carried out by an expert analyst; even if the supply is apparently sound, his opinion should be obtained for confirmation, or otherwise, of that formed by the engineer. The preliminary examination should have the good result of the rejection of palpably bad sources of supply; when properly conducted it is seldom that it is not supported by analysis.

(*c*) *Samples for Examination.*—It stands to reason that a sample sent for analysis should be truly representative of the water to be examined. If drawn from running water, the collection should be made when the stream is at its average flow and is not polluted by storm water, nor impaired by a prolonged drought when organic germs may exist in large number. If derived from stored water, it should be obtained at some small depth below the surface, so as to be free from surface and bottom impurities. If taken from a spring, it should be extracted from as great a depth as practicable so as not to be contaminated by dissolved surface matters.

It is essential that the bottles in which a sample of water is collected for analysis should be absolutely clean, and that they should be finally rinsed in the body of that water; glass-stoppered bottles are the best, but if not available, ones with tightly-fitting corks will serve, and these should not be sealed, as the wax or paraffin may introduce matters which will distort the analysis. For bacteriological examination the samples should be tested early before they deteriorate by storage.

As the presence of impurities by themselves may lead to wrong conclusions (e.g. chlorine may indicate sewage contamination, but also may be due to strata impregnated by inorganic salt, which is harmless), it is necessary that the analyst should examine the locality whence the water was obtained, or be furnished with a report of the local conditions. For a surface water scheme such report might give the following particulars :

(i) The distance from the source of the supply to the point of collection ;
(ii) What known pollution takes place, and if it does, its nature, and how far upstream it occurs ;
(iii) The geological nature of the catchment.

For a subsoil water scheme the particulars might be :

(iv) The depth below the surface at which the water was obtained ;
(v) The nature of the surface soil, sub-soil, and water-bearing stratum ;
(vi) Whether or not surface percolation is shut off by an impervious stratum overlying the water-bearing one ;
(vii) The sanitary condition of the neighbourhood.

In dealing with the nature of the catchment, and especially with the part near the source of supply, notes should describe if the area is inhabited, densely or sparsely, by human beings and animals ; is cultivated, uncultivated, or pastured ; is wooded or bare ; has or has not polluting manufactories, sewage works, etc.

As the analyst will thus be in possession of facts ascertained by inspection or from the report, so the engineer should be able to interpret the results of the analysis from a knowledge of what is indicated by each feature disclosed by it. Each should form his own opinion, and if they differ, they should consult each other, so as, if possible, to arrive at a joint conclusion; otherwise, the engineer should take the responsibility of making his own recommendation.

As water is constantly varying in quality, it is advisable to have several analyses made at different times, and if the water is considered not potable, and the source of impurity is not patent, to endeavour to ascertain that by introducing into suspected localities highly soluble and easily detected chemicals not naturally existing therein, such as common salt or fluorescin, and subsequently testing for them.

The different forms of analyses are chemical, bacteriological, and microscopic examination; none of them is absolutely perfect, and a combination of them, especially of the first two, is desirable.

(*d*) *Chemical Examination.*—The object of this is to discover if the water contains anything deleterious to health, and especially matters which may be evidence of sewage contamination.

Solids are separated by filtration, after precipitation, if necessary; they are either inorganic or organic. The principal of the former are carbonate of lime producing temporary, and chloride and sulphate of lime giving permanent hardness; also iron, which may exist in quantity objectionable to health and domestic use. The latter are due to vegetable and animal *débris*, and are detected by heating the fitrate, when they blacken it and give off fumes until they are driven off. The first named are usually stable, and may be innocuous; the second are liable to decay and decomposition, and are then dangerous, but it is difficult to differentiate them chemically; they may generally be classed as organic carbon or organic nitrogen.

Chlorine is evidence of sewage contamination, unless it is derived from the solution of saline strata, or is due to the proximity of the sea to the source of supply, when it is harmless, unless present in excess, rendering the water unpalatable.

Albuminoid ammonia is produced in the first stage of the decomposition of organic matter, so that early examination is desirable for its detection; it and free ammonia invariably accompany sewage, and then indicate recent contamination, but the latter may also be derived from vegetable matter, or be contained in rain or deep spring water, when it is not evidence of danger. The amount of albuminoid ammonia present is the most important indication of the degree of purity of the supply when the suitability of a water for potable purposes is under investigation.

Nitrites are due to a further decomposition of organic matter owing to incomplete oxidation, and indicate recent contamination; they are, however, occasionally produced by chemical changes in subsoils, which are harmless.

Nitrates are formed by the final oxidation of nitrites, and may evidence more remote, and possibly not dangerous, organic contamination. As such salts are stable, they may remain in the soil for a long time until dissolved out, and then do not indicate danger.

Organic impurities may also be detected by ascertaining how much oxygen is required to oxidise the carbonaceous matters in the water.

(*e*) *Bacteriological Examination.*—The object of this is to determine the presence of pathogenic (disease-producing) germs by qualitative analysis, and how their number varies from point to point of the supply by quantitative analysis; also to isolate such germs and study their effect on lower animals experimented upon. The water to be examined is first added to a culture medium, i.e. a solution furnishing food for germ growth. The different kinds of germs separate themselves in this and increase their numbers to form "colonies"; part of a colony is then placed in a previously sterile culture medium and allowed to develop for examination. The whole of the work connected with the investigation is of a delicate scientific nature, and has to be carried out by an expert, as the slightest error may lead to wrong conclusions being formed.

Qualitative analysis is the first which has to be carried out, as it is necessary to know what germs—pathogenic, harmless, or beneficial—are contained in the water; most bacteria are harmless. Thereafter, quantitative analysis is required to ascertain the amount of infection, and thus to compare one water with others, either from different sources of supply, or the same source at different points in its course, so as to select the most favourable intake. This form of analysis is particularly useful for testing the efficiency of filters in arresting the progress of germs; chemical analysis could not detect this, but only the presence of matters in solution, which would generally pass unchanged through the filters, or, possibly, might be partially oxidised thereby. As germs tend rapidly to multiply, the analysis of a sample should be made as early as is practicable after its collection.

Bacteriology is of comparatively recent origin, and its examinations are not yet perfectly reliable in their results, but they are continuously being improved.

(*f*) *Microscopical Examination.*—By means of this can be detected inorganic and organic matters in water, but not bacteria, which are invisibly small germs. The inorganic impurities do not affect the water sanitarily, but may prejudice its use for potable or non-potable purposes. The organic ones may be either of vegetable or animal origin; they may thus indicate sources of pollution, and these may further be defined by examination of the supply at different points in its course. While such matters are not usually dangerous to health, they may impair the colour, taste, or odour of the water, and so render it unfit for use.

(*g*) *Requirements in Water.*—Classifying waters as potable, domestic, and manufacturing, the requirements of the three kinds may thus be stated:

(i) *Potable Waters.*—These have been discussed above, first from the physical and then from the sanitary point of view; their effect on health, as distinct from disease, remains to be noted. It is well known that certain medicinal waters have a high curative value; others, on the contrary, are believed to be prejudicial owing to the salts with which they are charged to excess. Not only may these salts be contained in the natural water, but they may be produced during its passage through the distribution system, for when the supply is charged with carbonic acid gas (from vegetable decomposition, etc.) it has a solvent action on metals. Zinc may have a small poisoning effect, and lead a much greater one; iron in comparatively small quantity may affect the colour and taste of the water. Air and carbonic acid gas dissolved in water add to its palatableness.

(ii) *Domestic Supply.*—Water is wanted for cooking and laundry work, and for both soft water is desirable, as hard water ((*d*) above) injures foods and causes an unnecessary expenditure of soap.

(iii) *Manufacturing Supply.*—Different manufactures, such as brewing, dyeing, etc., require water of particular characteristics, and this often leads to the location of the factories where such can be obtained. The most generally prejudicial effect of water results in the boilers when it is hard (Art. 254 (*b*)); temporary hardness causes a friable deposit to form, while permanent hardness leads to a solid scale very hard to remove. Both cause expense by coating the boiler with a non-conducting skin, which, if it is allowed to become thick and then cracks, may cause an explosion when the overlying water is suddenly admitted thereby to the overheated metal.

(*h*) *Varieties of Water.*—Water may be meteoric, running, stored, subsoil, or distributed, and each kind has its peculiarities.

(i) *Meteoric Water* starts as perfectly pure rainfall, but in its course through the air may absorb various gases, such as nitrogen, oxygen, and carbonic acid in the country, and, as well, ammonia, sulphuric, nitrous, and nitric acids, and other gases in towns, and especially manufacturing centres. It may also absorb germs from the air; these diminish in number as the altitude is increased and habitation and cultivation are decreased. Thus reservoirs are best located high up streams and in non-occupied catchments. This class of water is naturally soft, and is liable to deterioration when stored; it is the source of all potable waters, and is derived from evaporation from the surface of bodies of water and damp soils.

(ii) *Running Water.*—The water in flowing down the bed of a stream receives the surface drainage of the land, and this may be highly charged with organic and inorganic matter, especially if there are peaty, forest, cultivated, or inhabited areas in the catchment. At the beginning of the rainy season in tropical countries this is particularly the case, for the surface has then been desiccated and undisturbed for several months previously, and its friable particles are discharged unchanged into the streams, the flow of which may thus be highly contaminated until that surface has been washed clean by prolonged downpours. Where crude sewage is admitted, the contamination will be all the more dangerous. Streams throughout their courses are liable to be fouled by individuals resorting for relief to their banks; thus surface waters are most likely to be polluted and most in need of purification. Inorganic matters may be due to the abrasion of the banks and beds of the streams. Moreover, when their water is charged with carbonic acid, it has considerable solvent powers on these substances. As inorganic are less dangerous to health than organic matters, a barren is preferable to a cultivated catchment.

A great defect of streams is that their flow is so irregular, and every increase of it may lead to further impurities being carried down. It is therefore necessary by numerous analyses to keep a watch on the characteristics of the discharge. Despite all these disadvantages streams are often utilised as sources of water supply; when this is done, the greatest care must be observed in the selection of the intake.

(iii) *Stored Water* is derived from running water, but its storage greatly improves it, partly by subsidence, partly by the great dilution of obnoxious matters, and partly by its power of self-purification, as fresh nutriment and oxygen are not provided for germs by the quiescent body of water, and they thus die and diminish. Occasionally it favours the increase of aquatic plants and growths, both on the bed and surface; depth of storage and cleansing of the bed may lessen these. When the storage is small and is covered, the lower forms of vegetable life die from want of light; all such reservoirs and wells should therefore be protected thus. Stored waters are naturally less liable to pollution than running waters, as they are subject to less land contamination. Vegetation is most profuse in shallow lakes, and odours may arise therefrom. A storage of four weeks' duration has been considered sufficient not only to get rid practically of all typhoid germs, but also of other harmful bacteria. As the duration of storage in a large reservoir extends to several months, the purification in it should be still more complete; this is one of the chief advantages of such works to water-supply schemes. Filtration of stored water may be more rapid than that of unstored water, as a well-stored, rapidly-filtered water is likely to be safer than an unstored, slowly-filtered water.

(iv) *Subsoil Water.*—This is likely to be the clearest of all kinds of natural water, as it has been purified by filtration through the soils, but at the same time it may be charged with dissolved salts; the efficacy of natural filtration depends not only on the depth, but on the porosity of the soil and its freedom from fissures extending to or near the surface. If surface water is excluded from it, its germ content will be very small; if, however, that is admitted to it, the germs are likely to increase rapidly, as they will have abundance of dissolved food, and are not so liable to the competition of other forms which occur in surface waters. Even deep wells may thus be infected, especially if they are not drawn upon; when this occurs before samples are taken for analyses the wells should be pumped for some time. Care should therefore be taken in insanitary areas to avoid having shallow wells, and to case off the top strata from the bottom ones of deep wells. For similar reasons it is not advisable to store subsoil water for any length of time owing to its liability to deterioration. On the whole subsoil water is one of the most reliable kinds, and is well suited to the requirements of small towns.

(v) *Distributed Water.*—The water in mains may be purified by the action of the iron on algæ, etc. When this happens the dead growths should be got rid of early by scouring, etc., so that they may not furnish food to pathogenic bacteria; this should be done particularly at "dead ends" which are stagnant. Water deficient in lime and magnesia salts cannot coat, and thus preserve the iron pipes; where these are in excess, however, they may reduce the bore and discharging capacity of the pipes. Water rich in iron may induce iron tubercles to form in the pipes, and these have a similar effect. Water charged with carbonic or other organic acid has a dissolving power on lead pipes, which may cause lead poisoning. It is difficult to tell beforehand what will be the effect of water in passing through the distribution system, and it is therefore advisable to keep a constant watch on it by means of analyses, especially if the health of the town suffers in any way which can be attributed to defects of its supply. On the whole it may be said that the action of pipes is beneficial.

Stored filtered water if kept for some time is likely to deteriorate bacteriologically for the same reasons as subsoil water, i.e. owing to the presence of dissolved food and the absence of competing organisms (see (iv) above).

(*i*) *Sources of Impurity*.—Various causes of impurity have just been mentioned; the chief danger lies in the introduction of pathogenic bacteria into the system, either by the direct admission of sewage, or by the drainage from cultivated lands; it is to remove them and improve the water generally that purification is required. The surface of such soils may be charged with bacteria, as it is abundantly supplied with light, warmth, and food. Lower down the subsoils have fewer and fewer germs, as the upper ones are strained out and the conditions for fecundity are very greatly diminished; but the water is more charged with organic salts. In addition to selecting the intake well away from any sewage inlet, it should be placed out of reach of contaminated surface flows, which may possibly be practicable by diverting them downstream of it. During storm flows this may not be feasible, and as these are the most infected, they should not be drawn on if that can be avoided. To assist in the selection of the best site of an intake, the neighbourhood should be examined by means of a sanitary survey, including such analyses as may be necessary. An intake should, of course, be situated well above the outfall of town sewage works.

(*j*) *Purifying Agencies.*—The principal of these are dilution, sedimentation, aeration, sunlight, germ competition, and, occasionally chemical reaction in flowing water. When sewage enters a stream or storage it becomes mixed with a much greater body of water, which, if more sterile, will diminish the growth of germs. In running water, and still more in stored water, the fine inorganic particles originally in it tend to fall to the bed, and in so doing to carry germs with them to lower levels, where they may die, but possibly may increase locally. In quick-flowing streams such deposited germs may be brought up again to the surface by eddying motion. Aeration improves a water (especially one impregnated with iron) by the oxidising effect of the air on it; it takes place best in quick-flowing streams, and also when waves are formed on reservoirs. The chemical rays of the spectrum destroy certain bacteria; to enable this to be done the water should be clear. Germ competition may take place between the numerous forms of bacterial life, but the result could not well be foretold in the absence of many analyses. It is probable that those forms have each their own particular food, and thus they are not competitive; but they may exhaust that food and thereafter perish; possibly they destroy each other by the toxic effects of their by-products. Several observers have pointed out that the pathogenic forms, being parasitic, are less well adapted to survive in water than the more truly aquatic saprophytes; and others that the vitality of pathogenic micro-organisms in water is in the inverse ratio of the numbers present. Chemical reaction will take place when a stream flows over a stratum which is acted upon by salts and acids already in solution in the water.[1]

Of all these agencies probably sedimentation in storage reservoirs is the most important, as, if sufficiently prolonged,[2] it reduces the number of all kinds of bacteria; it devitalises the microbes of water-borne disease; it reduces the amount of suspended matter and the amount of oxygen absorbed from permanganate; it tends to lengthen the life of filters, and minimises the possible danger arising from a breakdown in the filtering works. To secure the most favourable results at every stage of its treatment water should be drawn off from a little below the surface to avoid surface contamination and bed impurities; in small reservoirs this can best be effected by the use of floating pipes.

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[1] Minutes of Proceedings, Inst.C.E., Vol. CLXXXI, p. 18.

[2] Report of the London Metropolitan Water Board for the year ending March 31, 1910.

The question in what distance the agencies will enable a sewage-contaminated river to purify itself has led to great difference of opinion; some consider that this action will take place perfectly in a course of about 12 miles if the volume of the sewage is not greater than 5 per cent. of that of the stream, while others believe that the germs may travel down from the source to the sea outfall. Much must depend upon the character of the river and of its infection, but seeing a stream is liable to pollution all down its course, it would seem better not to take the self-purification for granted, but to watch it by means of analyses and to adopt immediate steps to deal with any contamination detected thereby.

(*k*) *Classification of Waters.*—The Rivers Pollution Commissioners, England, classify waters thus:

Wholesome	Spring water	Very palatable
	Deep well water	
	Upland surface water	Moderately palatable
Suspicious	Stored rain water	
	Surface water from cultivated land	Palatable
Dangerous	River water to which sewage gains access	
	Shallow well water	

Palatableness is by no means a reliable indication of the suitability of a water for drinking purposes; cases have been known where sparkling, palatable water has obtained those characteristics from sewage contamination.

250. Water-borne Diseases.

(*a*) *General Remarks.*—Water-borne diseases are those which are communicated to the body by water containing their germs, which generally develop in the intestinal canal; such germs may, however, also affect solid food or milk (the infection being usually conveyed by flies), and will then produce the same effects. It has therefore to be carefully considered if a contemplated water supply is free from or liable later on to infection; also, whether the pathogenic germs are likely to multiply in the water, and for how long they can maintain their vitality and activity. These last conditions depend greatly upon the amount of organic nutriment in the water, and also on the presence of bacteria harmless to man, of which the by-products may have a harmful effect on the ones dangerous to him. Generally, the amount of that nutriment is insufficient to allow of great multiplication of the germs, and thus most kinds of them after some time die for want of it. When, however, the conditions are favourable to development, possibly a single pathogenic germ, and certainly one infected evacuation, introduced into a supply system may by rapid germ multiplication lead to the outbreak of an epidemic, so that the greatest care must always be taken to conserve the system perfectly.

The principal water-borne diseases are typhoid fever (in the West), cholera (in the East), dysentery, diarrhœa, anthrax, and malaria. Certain parasitical worms are also introduced into the body by their eggs entering water in the discharges of infected animals; of these guinea-worm is prevalent in the tropics, and is found in shallow wells used for bathing as well as drinking.

(*b*) *Typhoid Fever*.—The germ which produces this is the *Bacillus typhosis*; it is so greatly similar to the *Bacillus coli communis* that some consider the two identical, although most believe them to be distinct organisms. The latter is always present in the intestines of men and animals, and its presence in water is practically conclusive evidence of sewage contamination. Towns are frequently situated on the banks of rivers for facility of water supply, but as they discharge their sewage effluents into the rivers, they thus may contaminate the water. As the population increases, so does the danger from this cause become greater. In the case of such towns an outbreak of typhoid, due to sewage contamination of the water supply, may easily be communicated from one upstream to others downstream of it, and this increases the necessity for preventing an epidemic. Wells, especially open and shallow ones, are also liable to be infected, particularly if they are private ones and not under close sanitary supervision. The number of cases of typhoid is an indication of the comparative purity of the water supply, as the mortality in towns from this cause decreases as that supply is sanitarily improved. The vitality of the typhoid germ lasts for several weeks in potable water, and longer in cold than in warm water, and in wells than in surface water, although that contains more organic matter. As a rule, cases of disease increase from the late summer to the winter, and then decline to the spring.

(*c*) *Cholera.*—The home of this disease is in the East, but it may be introduced to western lands if quarantine is faulty; it is due to the cholera spirillum, which develops rapidly in the intestine, and thus occurs in profusion in the evacuations of those attacked. In India it is liable to break out during pilgrimages, when are collected together large numbers of persons exhausted by travel and defective food supplies, and to be carried all over the country as the crowds disperse. A good temporary water supply and proper sanitary regulations have there been found the best preventives of outbreaks. For the rapid increase of germs organic matter in solution is required, and thus their vitality is greater in polluted than in pure water; it is also increased in brackish water. Some experimenters have found that the duration of vitality lasts only from one to three days; others from seven to thirteen days; and others, again, that it extends to several months. Outbreaks of cholera are usually short, but very severe; they may take place at any time, but chiefly in the hot weather; the period of incubation lasts from one to five days.

(*d*) *Dysentery.*—In the tropics this disease is most severe, and is believed to be there due to an animal parasite, *Amœba coli;* in more temperate regions it is less severe, and is thought to be caused by various bacteria, which, however, have not been definitely determined to exist in water supplies.

(*e*) *Diarrhœa.*—This may be produced by organic matter of either vegetable or animal origin. In certain cases the producing germ resemble the comma bacillus of cholera.

(*f*) *Anthrax* primarily attacks cattle, but may be communicated by them to human beings by the surface drainage from lands infected by them rather than by sewage contamination. It is thus more likely to be derived from river than other supplies. The germ, *Bacillus anthracis*, differs from the others described above, in that it can form spores. In its sporeless stage the germ has a vitality only from two to five days, but the spores themselves are much longer lived, and many exist for over a year, especially in low lands subject to overflow.

(*g*) *Malaria* is introduced into human beings by the bite of the Anopheles mosquito, which in the tropics breeds freely in even small collections of water. There, as a necessary precaution, all pools, etc., should be drained, and water stored in service reservoirs should be protected by fine wire gauze to prevent the ingress and exit of the insects.

251. Conservation of Reservoir Catchment and Basin.

(*a*) *The Catchment*—(i) *General Remarks.*—The only absolutely safe gathering ground would be one consisting entirely of uninhabited, uncultivated, unpastured, and barren soil or rock of an insoluble nature. Such can practically never be found, and it is therefore necessary in a good water-supply scheme dependent upon a storage reservoir to have recourse to filtration to remove the defects due to the nature of the drainage area. It is, however, most desirable to have and maintain the catchment as sanitarily perfect as possible. The expense of the acquisition of the entire area will in most cases be prohibitive, but it might be practicable, and would then be advisable to acquire not only the basin of the reservoir up to high-flood level, but also a zone of some width round it so as to conserve its margin. Also, it may be possible to obtain legal protection of the catchment so that deleterious trades may not be established in it, extra collections of men and animals may be prevented, and, generally, that it may be conserved sanitarily; if this can be arranged, it should be (Art. 257 (*a*) (iii)). The ordinarily most harmful thing in a catchment is a collection of human inhabitants with their animals, and the pollution from these increases with their number and their nearness to the reservoir or to its tributary streams. In hill districts, in particular, in many parts of the world, where the sources of water supply have been opened freely as grazing grounds, it has been observed typhoid has been common. The fact that milk is a frequent source of infection points to the probability that it has been infected by the germ owing to the animals drinking from water polluted by their own dejecta. To prevent men and cattle having direct access to the reservoir it should be securely fenced, and separate watering places should be arranged for them. The use of nightsoil manure in the catchment should also be prohibited.

(ii) *Treatment of Inhabited Areas.*—Probably the simplest effectual way of dealing with a village in a catchment area would be to surround it by an embankment, or by catchwater drains, so as to cut it off from direct water communication with the reservoir. The drainage from this area would then be led to a small tank with a storage capacity equal to at least one-fourth of the maximum annual yield of its catchment; this storage could be utilised for the irrigation of fields, also embanked round, and the tank thus emptied when necessary, say, four times during the year. The embankments round the village and the area to be irrigated and the dam of the small tank would all have puddle trenches under them so as to be water-tight. During the fair season the bed of the tank and the irrigated lands under it would be ploughed up and allowed to desiccate. The irrigated area should be acquired, and might be let out on liberal annual leases, coupled with the condition that the lessees would be held responsible for the proper working of the system.

In the case of a village situated on the bank of a stream a possible treatment might consist in constructing two low intake weirs, upstream and downstream of it, with channels from them. The downstream channel might lead into a tank as just described, while the upstream one could be allowed to discharge into a drainage line outside the village and communicating with the main reservoir. The object of the latter is to divert small flows from the former, and thus to prevent the too-rapid filling of the tank. During heavy rainfall the upstream weir may overflow, and then the downstream channel will of course not be able to divert the whole flood, but by the time the discharge of the stream increases beyond the capacity of that channel the village area will probably have been washed fairly clean, and the run-off therefrom direct into the main reservoir will most likely be only slightly contaminated, and the impurities thus largely diluted will be practically innocuous.

During the construction of the storage reservoir the work-people should be camped below the dam, and should not be allowed to resort upstream of it for natural purposes.

(iii) *Diversion of Contaminated Flow.*—As in the tropics the earliest flows at the beginning of the rainy season are most heavily charged with the washings of the surface, they consist of water not fit for potable purposes. If they can be diverted from entering the reservoir, they should be; but as this will rarely be possible, the next best arrangement will be to pass them out of it at a low level by then keeping open large sluices constructed for the purpose in the outlet. Thus this highly polluted water will not rise to a high level, will not have time to deposit most of its silt on the bed, and will not remain in the reservoir so as to contaminate its future upper storage, which only should be drawn upon.

(*b*) *The Basin.*—In Article 249 (*i*) it has been noted that in soils organic matter is concentrated at the surface, and decreases rapidly in amount with the depth below it. Where practicable, it is therefore advisable to remove the top soil, and it may be possible to utilise this in the construction of the dam. Where such stripping cannot be carried out, it should be feasible to plough up the entire reservoir basin and allow it to desiccate during the whole time the works are under construction; all growing vegetation should also be burned. Every year thereafter, as the water surface falls, the area thus laid dry should be treated similarly. The earlier falls of rain will, moreover, thus be able to wash down some of the soil so pulverised into the lowest part of the basin, and this transference may be assisted by scraping the soil towards that part. In Article 257 (*a*) (iii) it is stated that where there are two reservoirs at the head of the system they will permit such work to be carried out easily. By arrangements of this kind the sanitary condition of the bed should be improved at not very great cost.

The proper sanitary conservation of all catchments of other intake works is, of course, equally necessary, and every precaution possible should be taken to ensure it, both while selecting the sites of the intakes and after their construction, when the waterworks of which they are the head are in operation.

252. Sedimentation.

(*a*) *General Remarks.*—Sedimentation is the process by which matter mechanically suspended in water is deposited by the action of gravity; it takes place at a rate directly proportional to the specific gravity and size of the particles and inversely proportional to the depth and velocity of the water. Sediment varies in character and amount in a stream with the depth and velocity of its discharge and the geological nature of the catchment it drains; this variation constitutes a difficulty in dealing with the water by arrangements made to ensure sedimentation. In streams utilised as sources of supply the sediment consists chiefly of inorganic matter, principally sand and clay, and some organic matter mostly of vegetable origin, on both of which the turbidity of the water depends. There are also present bacteria (of which some kinds are dangerous to health) in numbers which are actually greatest when the stream is in flood (caused by the run-off of rainfall from the surface of the catchment), but are relatively greatest in proportion to the volume during times of low water, although the discharge is then clear. The rate of deposit in streams depends upon their velocity; in slow-moving ones it will be steadily progressive, but in quick-moving ones will be irregular, as eddies will bring towards the surface matter which was descending to the bottom. Sedimentation takes place regularly in quiescent reservoirs of large and small size, and at a rate which depends upon the character of the suspended matter and the depth of storage, and has to be determined by experiment. Sedimentation improves the appearance of the water by clarifying it, and is thus specially necessary for dealing with flood waters. It also increases its potability by lessening the number of the bacteria, as many of these are carried down with the grosser particles and deposited on the bottom, where, however, they may live for some time when the storage is shallow. It does not remove all the bacteria, and therefore by itself cannot be depended upon to make the water safe for drinking purposes, but is a valuable aid and first step to the final process, filtration, by which polluted water is rendered potable.

The rate of settlement depends upon the size and shape of the particles, since their weights are proportional to the cubes, whereas their surface areas are proportional to the squares of their diameters. Thus turbid waters soon deposit the coarsest suspended matter; the finer particles may require months to be precipitated, while the finest may remain in suspension indefinitely. The large particles in their descent entangle some of the finer ones, and carry these down with themselves; thus the addition of turbid to fairly clear water may lead to quicker sedimentation of the latter. Turbid waters are more improved by sedimentation than are clear ones, both in respect of solid particles and also in that of the bacteria deposited with them.

(*b*) *Settling Basins.*—The works in which sedimentation takes place are called "settling basins." They are hardly required when the water is drawn direct from a storage reservoir, but are generally wanted when it is derived from a canal or stream, in which case that is usually pumped into them after having been passed through strainers to remove *débris*, etc. The total size of the basins should be sufficient to give the necessary time for the improvement of the water by storage, and may also be made so as to provide storage capacity available for use when flood waters are excluded and not drawn upon. As much as fifty-six days' storage has been proposed for the heavily polluted London supply; the usual practice in England is to allow for two or three days' storage, and in America, one day's storage. The basins are arranged in series so that any one of them can be thrown out of use for cleansing, etc. Their beds should be formed of concrete smoothly finished off, and each sloped down to a central drainage channel; the sides may be vertical, or sloped and concreted. The deeper the basins, the less ground will they occupy, and the cheaper will they be to construct, but the longer will the water take to settle in them. Although it is stated by some that the time of settlement is not materially affected by the depth, others consider that the period allowed for it should be some multiple of that taken by the particles to fall through the water. Probably a depth of from 10 to 12 feet will be suitable; some works have been constructed from 16 to 20 feet deep. The sediment will be charged with live bacteria rapidly increasing in numbers, and should therefore be removed early; the deposit can be flushed into the central drain by means of a hose, and the more frequently this is done, the easier will be its removal.

Sedimentation can be made to take place either by continuous or by intermittent flow. In the former the water is distributed on entry as evenly and as gently as possible at one end, and is drawn off similarly from the opposite end of the basin, and from near the surface. The flow throughout should be imperceptibly slow and perfectly gentle, so as not to disturb the sediment being precipitated. A very small loss of head is thus caused. In the latter the water is let into each of the basins and remains quiescent therein for the time ascertained to be required for sedimentation; the clarified water is then drawn off, and the basin refilled. The loss of head in this case is great, being that of the depth of water drawn off from the basins. An advantage of this form is that the basins can be utilised for temporary storage; a disadvantage of it is that when water is being drawn off from the bottom there is a chance of the underlying turbidity being carried up and passed out with the clear supernatant storage.

253. Coagulation.

(*a*) *General Remarks.*—Coagulation is the process by which matter mechanically suspended in water is deposited by the action thereon of chemicals producing a gelatinous precipitate which falls to the bottom at the rate of about a foot an hour. It is thus a development of the slow process of simple sedimentation, and is best effected subsequently to it. Owing to the sticky nature and greater volume in larger masses of that precipitate it carries down with it more bacteria than does sedimentation, and is thus more efficient than that; this is its principal utility. Coagulation is chiefly employed in combination with quick-acting mechanical filters, and its use alone makes them practicable. It is, however, also used in connection with slow-acting sand filters, and is so beneficial in developing the surface scum on which filtration by them depends that it may well be generally applied to water before it is passed through them; to allow the surface scum to form quickly the treated water should be admitted to the filters before it is entirely clarified in the coagulating basin. In addition to removing turbidity and bacteria, coagulation can reduce coloration in water when that originally exists in small amount.

The quantity of coagulant required has to be determined by experiment. In order that the coagulant may act properly, the water treated should be "alkaline," that is, should possess "temporary hardness" (due to the carbonates of lime, magnesia, or soda), or should have lime or soda carbonate added to it. The alkalinity produced by magnesia is only about one-half as effective as that by lime or soda. The result of coagulation is that "temporary" is replaced by "permanent hardness" (Art. 254 (*b*)), and carbonic acid is set free in the water, thus rendering it more palatable but less suitable for boilers and most trade purposes, and more likely to attack unprotected metals. The increase of permanent hardness is, however, small; it can be prevented by using soda carbonate instead of lime carbonate. The coagulant salt may be placed on a tray in a solution chamber and the water made to pass through this and into the coagulating basin.

(*b*) *Alumina Sulphate.*—This is the coagulant chiefly used. When added to alkaline water it breaks up into sulphuric acid, which unites with the alkali (to form sulphates of lime or magnesia, and thus increases permanent hardness), and aluminium hydrate, and it is this last that forms the gelatinous flocculent precipitate which purifies the water; it settles at a rate of about 1 foot an hour. There should be sufficient alkali present naturally in the water; otherwise lime should be added to it so that the coagulant may react properly. If the water is turbid, the clay particles unite with some of the aluminium hydrate and prevent its coagulation; if it is very turbid and contains little alkalinity, the addition of lime will be necessary to make it sufficiently alkaline. As much of the turbidity as possible should therefore be removed by sedimentation before the coagulant is added.

Common alum is the double sulphate of alumina and potash, and as it thus contains only half as much alumina (on which coagulation depends) as the simple sulphate, and costs as much, it is less efficient and dearer than that. As, however, of the two salts it can generally be more readily obtained, it is used domestically, and with good results for clarifying water.

(*c*) *Ferrous Sulphate.*—This coagulant is less frequently employed than the alumina salt, as with it it is generally necessary to add lime, etc., to increase the natural alkalinity, and this makes the process more intricate and mistakes more probable. The ferrous precipitate is the better of the two, as it is heavier, and is produced in larger masses and more quickly, while clay and other substances causing turbidity do not affect it; moreover, an excess of it is less likely to prejudice the public health than is an excess of alumina. The disadvantages are that the water thus treated is less sparkling and palatable, as the addition of lime in the process deprives it of free carbonic acid gas; also, vegetable colouring matters may combine with the iron salt, and are then not easily dealt with.

(*d*) *Anderson's Revolving Purifier.*—In this apparatus iron filings are revolved for from three to five minutes in the water to be purified, and thus a small amount of iron is dissolved by the carbonic acid in the water to form ferrous carbonate. This is subsequently oxidised by aeration of the water into ferric hydrate, which acts as a coagulant in removing colour, and especially bacteria, without increasing the hardness of the water. The coagulated matter is subsequently precipitated in settling ponds, and the water is filtered through sand, or is strained off by filtration alone.

254. Purification.

(*a*) *General Remarks.*—Purification processes are those which are carried out in order to remove dissolved constituents of raw water which may render it unsuitable for potable, domestic, or manufacturing purposes, or injurious to the distribution system. As they all involve skill and care in manipulation, they are more likely to be adopted for large than small schemes, and in highly civilised communities than in less advanced ones. For the latter of such schemes and communities it is generally advisable to endeavour to select sources of supply which are naturally good and do not require such improvement. For the former the cost of a near scheme requiring treatment should be compared with that of a more distant one with naturally good water, and the latter preferred, if not unduly expensive. The principal processes are noted on below.

(*b*) *Water-softening Processes*—(i) *Temporary Hardness.*—There are two kinds of hardness—temporary and permanent; the former is due to bicarbonates of lime and magnesia, which are held in solution by carbonic acid gas dissolved in the water. When the water is boiled (for cooking, washing, or trade purposes) this gas is expelled; thus the carbonates cease to be soluble and are precipitated. In Clark's process the same result is obtained by adding a small excess of lime, usually in the form of lime-water (produced by dissolving slaked lime in water), to combine with the carbonic acid gas, so that both the carbonate of lime thus newly produced and that formally held in solution are precipitated, and the whole of the temporary hardness is removed. When bicarbonate of magnesia is present, for its removal is required the addition of about double the amount of lime to that necessary for the deposition of bicarbonate of lime. These untreated bicarbonates when precipitated by boiling impair the flavour of certain foods, cause a large waste of soap in the laundry by curdling it,[1] and produce a soft deposit on boilers (Art. 249

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[1] The introduction of soft water of 1° of hardness from Loch Katrine is estimated to have saved Glasgow £36,000 worth of soap annually.

(*g*) (iii)). In Clark's scale the number of degrees of hardness of a water is equivalent to the same number of grains of carbonate of lime dissolved in 1 gallon of pure water, which precipitate the same amount of soap, i.e. each degree is equal to 1 grain of chalk dissolved in 1 gallon of water. One grain of carbonate of lime will precipitate about 8 of soap. When water possesses more than 5° of hardness it is usually called " hard " ; by Clark's process as much as 15° of hardness may be removed ; up to 16° of hardness is not harmful to health. The pulverulent precipitate of carbonate of lime carries down with it some bacteria, but generally much less than does the flocculent precipitate produced by alumina sulphate. In some cases the purification has, however, been equally high by the former as by the latter.

(ii) *Permanent Hardness.*—This is due to other salts of lime and magnesia, such as the chlorides, nitrates, and sulphates, which are not precipitated by the expulsion of carbonic acid gas dissolved in the water. They can, however, be removed by the addition of carbonate of soda, which forms with them soluble salts and precipitates the lime, etc., as carbonate. This permanent hardness produces by long-continued boiling a very hard, compact scale, especially if other matter is suspended in the water.

(*c*) *Removal of Iron.*—The ground waters contaminated by iron may be one of the three following classes :

Those which when aerated precipitate the iron.

Those which retain the iron in solution even when aerated. This kind of iron is usually combined with some vegetable acid, and appears in a colloidal form.

Those which contain both of the above descriptions of iron, and therefore precipitate part, but not all, of the iron after aeration.

The iron is due to the action on its salts in the soil (which exist generally in the form of ferric oxide) of water containing organic matter, that reduces them to ferrous oxide by abstracting oxygen from them, and thereafter the carbonic acid in the water combines with the iron to form soluble ferrous carbonate. This, if exposed to aeration, is oxidised, and is precipitated again as ferric oxide, which can be removed by filtration through sand. Where the carbonic acid is in excess, it can be neutralised by the addition of lime; where the iron exists as a sulphate, it can be treated with lime and alumina sulphate, or ferrous sulphate, or ferric chloride.

The objections to iron are that it may affect the taste and appearance of potable water, and render it astringent. It may make iron mould appear in laundry work, and may cause the iron *Crenothrix polyspara* to grow rapidly, and produce in the distribution pipes tubercles which seriously interfere with the discharge.

(*d*) *Removal of Colour.*—Colour is chiefly due to contamination of the water by decaying vegetation; when accompanied by iron, that should first be removed. The sources of vegetable coloration, if limited and defined, should thereafter be got rid of by clearance. If the coloration is extensive, it should be dealt with by aeration, treatment with metallic iron, or other coagulant (Art. 253 (*a*)), and finally by filtration.

(*e*) *Removal of Odours and Tastes.*—These are generally due to the decay of aquatic plants and animals, and are most frequent in hot climates. The water may be treated as for the removal of colour, or by copper sulphate as a solution of one part per million or less, which has a remarkable toxic effect on the lower forms of vegetable growth, even when very dilute; it is best to treat the water twice or more often with dilute solutions than only once with a strong one. The chemical destruction of algæ is, however, usually followed by considerable development of bacteria owing to the larger amount of organic food thus placed at their disposal. Copper drinking vessels give protection against cholera and typhoid, and this no doubt explains why they have been used in India from time immemorial. Aeration is particularly useful in dealing with defects due to offensive gases; it may be accomplished by forcing air into the mains, by letting the water descend by a series of weirs or cascades, or by spraying it in fountains. Aeration is, however, not effective in respect to ordinary purification; even the Falls of Niagara produce but an insensible betterment.

(*f*) *Sterilisation.*—This consists in attacking impurities in water by chemical reagents or by boiling. The action of various chemicals as applied in general treatment has been noted on above. Others, such as ozone, chloride of lime (bleaching powder), and peroxide of hydrogen may also be employed on a large scale, but are chiefly used on emergency when there are outbreaks of epidemics. Sterilisation after coagulation produces the best results, and is particularly useful in lessening the burden on filters by removing as much obnoxious matter as possible before the water is passed through them.

In India shallow wells suspected of contamination by cholera are purified by stirring permanganate of potash in them and washing their sides therewith until the red colour of the solution remains permanent; after the coloured water has stood in them for some hours, it is drawn out, and, if necessary, the process is repeated.

(*g*) *Domestic Treatment.*—In households great faith is often placed in filters, which are assumed to have a magical, automatic purifying capacity, whereas ordinary ones not properly maintained are really dangerous when concentrating the bacteria, as they may easily do if neglected or entrusted to servants to work. The two best varieties are the Berkefeld (quick-percolating) and Pasteur (slow-percolating); as both collect bacterial skins on them, they should be thoroughly cleansed once a week and sterilised by boiling.

Simple boiling without subsequent filtration (which may reinfect the water) is the best domestic treatment, as no pathogenic germs likely to be met with can withstand boiling for more than ten to fifteen minutes, while cholera and typhoid germs are killed by it in five minutes. The water should be allowed to cool in vessels, also sterilised by boiling, and, when cool, may be rendered more palatable by aeration and the addition of a little common salt.

255. Filtration.

(*a*) *General Remarks.*—Filtration is the final process by which water is purified to render it safe and free from defects and agreeable to smell, sight, and taste; it is required for practically all kinds of water except deep-seated ones, but chiefly for surface water, as that is most subject to contamination. Good filtration removes pathogenic bacteria, objectionable odour, colour, turbidity, flavours, and certain chemical impurities, and thus permits of the use of a less perfect water than would otherwise be advisable as a source of supply. Before filtration is commenced, sedimentation and coagulation should take place, and also sterilisation, if necessary, as all these act as aids to it, and, by reducing the burden on the filters, conduce to their better and longer working.

The elimination of a dissolved salt by filtration has been shown to be inversely proportional to the concentration of the solution. Thus a 1 per cent. solution cannot in one operation readily be reduced beyond a 0·5 per cent. solution, while the latter can by subsequent filtration be reduced to a 0·025 per cent. solution. This fact is taken advantage of in certain processes and works; in the latter preliminary filtration is performed near the storage works to lessen deposits in the supply aqueduct, and final filtration near the service reservoirs. Occasionally, double filtration is practised at one site, the water, when it is considerably polluted, being passed twice through the filters, or from one bed to another when the working of the former is started. Arrangements should be made, if necessary, that the second filter bed is supplied with sufficient sediment to make it biologically efficient. The Puech-Chabal system of multiple filtration successively over beds of fine gravel, a coarse sand filter, and lastly a fine sand filter, produces regular and uniform bacteriological results, and obviates the necessity for storing water to purify it.

Filters are of three types—(i) Slow sand, (ii) intermittent, and (iii) mechanical. Of these the first is the longest established, and is generally considered the best, the second is seldom used, and the third, which is of recent origin, has certain defects that are being removed. In all of them sand plays the chief constructional part; it was originally adopted only to remove turbidity by its straining action, but while successfully effecting this, was found greatly to improve the quality of the water; this is now known to be due to its action in connection with bacterial life by which almost all disease germs are destroyed in their passage through it.

(*b*) *Location of Filters.*—Filtration being the final stage of purification, it is essential that after it has taken place contamination of the supply should not occur. For this reason the filters are often located near the town served, and this also facilitates the supervision of their working. When the source of supply is a somewhat distant reservoir, it may be advisable, on account of the more adaptable ground levels and cleaner surroundings there, to place the filters near the head of the supply main; that main, being water-tight, should preserve the supply in it uncontaminated. Occasionally untreated water contains dissolved or suspended matter, which may act on the pipes and cause them to deteriorate or to be blocked by sediment or growths (Art. 260 (*a*)); in such a case the purification of it to remove such defects at least should be carried out near the intake. With near supplies the water will generally have to be lifted by high-lift pumps for filtration and distribution. With distant supplies it may have to be raised by low-lift pumps for filtration, and may then flow by gravitation; or, if the levels permit, it may pass by gravitation throughout the whole waterworks system.

(*c*) *Biological Action of Filtration.*—When water which is slightly turbid and contains bacteria reaches a filter, a deposit, or skin (schmutzdecke), of organic germs entangled in the products of the cells themselves and vegetable *débris*, and of inorganic matter, is gradually formed on the surface of the sand. It is this skin which chiefly leads to the bacteriological purification of the supply, for in it the pathogenic germs are consumed by other living organisms. While filtration proceeds the thickness of this film increases, and the upper layers of sand become more impervious, thus reducing the rate of percolation, until, if the action is unduly prolonged, they would stop that. As the skin and clogged layers get thicker, so does their purifying effect become greater.

The individual grains of sand for some depth below the bacterial skin get covered with a glutinous coating of organic origin (zooglea) in which the pathogenic and other germs which pass through the skin are caught and mutually destroy each other. In order that this action may have full effect, it is necessary that the layer of sand should be of some thickness; it is not yet known whether the skin or the coating is the more efficient, but it has been established that both are requisite to ensure bacteriological purity. When the skin and the upper layer of sand are removed in the process of cleaning the filter, dependence for purification has at first to be placed entirely on the coating until the skin is re-established on the new surface; up to the time that the skin is formed purification is less perfect, showing that the coating by itself is not sufficient to destroy all the germs.

The sand does not act solely as a mere mechanical strainer; its interstices are far too large to arrest the germs, and even when fine sands are used they do not effect sensibly more purification than moderately coarse ones. Nor would the process of working by itself improve the sand, except perhaps in a very small degree by consolidating it, and such improvement would not take place at the quick rate resulting from the growth of the bacterial skin. It is found better to use the washed old "ripe" sand removed from a filter than entirely new sand of the same inorganic character; that is because the former still retains some of its organic coating. If the sand is sterilised, the effluent may contain more bacteria than the unfiltered water, owing to the development of the germs in the sterilised sand. If the sand freezes in winter, the beds are not likely to be properly cleaned, and then the effluent will have more bacteria than in warmer weather, when that operation is thoroughly carried out, although in winter the raw water has fewer organisms. These facts show that the efficiency of a filter depends upon its biological and not on its mechanical action. Moreover, the chemical changes which occur in filtration cannot be attributed to ordinary chemical action, for although there is some simple oxidation of the organic matter by aeration, the water passes through the interstices of the sand too rapidly to allow much to take place; these changes are caused by living organisms in the filter. The utility of the sand consists in its acting as a support to the bacterial skin and in its grains forming nuclei to which the coating can adhere. In its turn it is supported by underlying coarser sand and gravel graduated in size to prevent the upper material from being carried into the drains at the base of the filter which collect and deliver the effluent.

(*d*) *Rate of Filtration—Slow Sand Filters.*—In England the vertical rate of filtration usually varies from 8 to 12 feet a day (2·6 to 3·9 million gallons per acre) through the filter. The London rate varies from 2¼ to 4 inches per hour. A rate of 4 inches per hour gives a filtrate of 2,178,000 gallons per acre per day, and thus about 2,200 square yards of filter are required per million gallons a day. The slower the rate, the more efficient is the filtration; and the better the natural water, the greater the rate of filtration permissible. While this is true, it has been found that in certain conditions a moderate increase of rate does not lead to much decrease of efficiency. What is more important is to preserve the steadiness of the rate, for sudden fluctuations in it may cause the rupture of the bacterial skin; when change of rate is necessary, it should therefore be gradually effected. The best plan with new filtration works is to start working them at a moderate rate of 3 to 4 million gallons per acre a day, and to increase this slowly as experience dictates. The filters most sensitive to change are those having a small depth of sand, or the sand of which is coarse, and those which have been recently started, all of which is evidence of the necessity for developing and maintaining good bacteriological conditions.

(*e*) *Filtration Depth and Head.*—In England the depth of water over the sand is from 3 feet to 3½ feet, so that the water may not get too warm. Warm water is not only disagreeable for drinking, but may encourage the activity of the germs in the bacterial skin to an undesirable extent; it would therefore appear advisable in the tropics somewhat to increase the depth in the case of uncovered filters.

The head consumed in filtration, i.e. that necessary to force the water through the sand at the desired rate (Fig. 143, p. 611), is only a few inches with newly-started filters. It may increase up to from 2½ to 4 feet as the sand gets more clogged; the limit of head consumed is not only fixed by that available, but also by the condition that an excessive amount must be avoided, otherwise there is a danger that it may rupture the bacterial skin. The maximum filtration head can be determined from the experience of existing installations and the nature of the sand used in the one being started, and a margin of safety should be allowed. After clogging of the filter has continued regularly and slowly for some time it increases rapidly, which is an indication that the bacterial skin is thickening unduly, and the upper layer of the sand is becoming choked and impervious for too great a depth. The working of the filter should be stopped before this takes place, and to enable this to be done means should be provided for measuring the filtration head. Such means may consist either in placing the discharge regulating chamber in free communication with the water below the filter, or having for the purpose a separate chamber, in which the difference of head upstream and downstream of the filter can be measured by reading floats registering it. The latter system is simpler, as it obviates adjustments and repairs to delicate regulating apparatus, and therefore seems better for small installations in not highly developed countries. A knowledge of the filtering head consumed is also desirable when starting a filter, as its amount is in proportion to those of the bacterial skin and coating. Should there be very little loss of head, it will be an indication that these are deficient for safe working; the water should therefore be passed at a slow rate through the filter and run to waste until the organisms have developed sufficiently.

(*f*) *Sand for Filters.*—The sand should not contain any clay, dust, or organic impurities, nor should it disintegrate under the action of air and water; the grains may be sharp or rounded. It may contain up to 2 per cent. of the carbonates of lime and magnesia, and the former salt is sometimes added to it as lime powder when the water to be treated is acid; for alkaline water the addition of these salts is objectionable.

The finer the sand, the more efficient is it in removing bacteria, but the quicker is it likely to become clogged and require scraping; coarse sands allow such clogging to penetrate more deeply, thus necessitating an increase of the thickness which has to be scraped off. Fine sands produce uniformity and steadiness in working, but increase the filtering head; the "effective size" (Art. 209 (*a*)) of the sand should be about 0·012 inch diameter. The sand should, however, be fairly uniform, as in the process of washing it the finer grains are liable to be removed. Uniformity in each layer is also necessary in order to ensure regularity of filtration; the finest layers should be at top, as an underlying fine layer will cause the upper ones to choke more rapidly.

The thickness of sand varies from 2 to 4 feet, but is not usually greater than 3 feet; within these limits the thicker the sand the more regular and efficient is the filtration, and the longer the time the bed can be used before entire removal. The more polluted the water, the thicker should be the sand; the thicker the sand, the greater is the filtration head, and hence the amount of pumping that may be required. The thickness should not be reduced by scraping to less than 1 foot, but a minimum of 2 feet is better. The individual scrapings vary from ½ to 1 inch in thickness, and take place as the limit of permissible filtration head is reached; this on an average is about once a month. They are made by broad thin shovels, after which the drained underlying sand may be loosened by a fork for from 8 to 12 inches in depth, and thereafter the surface is smoothened by toothless wooden rakes. After scraping has been effected, the biological efficiency of the filter will be reduced until the bacterial skin is re-formed on the new surface.

Sand washing is effected generally by means of ejectors, which are of hopper shape; the sand is forced up by water pressure from the bottom of one into the top of the next ejector. Another sand-washing plant consists of an open-ended, slightly conical drum placed horizontally; the dirty sand is put in at the larger end, and is gradually conveyed to the smaller one by interior screw blades revolving against a current of water admitted in the reverse direction. In India the washing is effected by placing the dirty sand at the downstream end of a shallow rectangular masonry cistern and working it by shovels to the upstream end against a reverse stream of water.

The washed sand is called "ripe" in distinction to "raw," the name given to entirely fresh sand. The former is better for use than the latter, as its grains have a certain amount of organic coating, and therefore earlier start bacterial purification; thus old filters are better than new ones, and those that have been working a few days than ones recently scraped. If the washing removes an undue proportion of the finer particles of the sand, on which its filtering action chiefly depends, the "effective size" should be restored by the addition of sufficient new fine sand. All sand should be washed before it is taken into use.

Occasionally patented preparations, such as polarite and ferrozone (the former a magnetic oxide of iron, and the latter consisting of magnetic oxide of iron and salts of alumina and magnesia), are placed in layers in the ordinary sand of filters; they increase its efficiency and permit of a higher rate of filtration.

(*g*) *Filling Filters.*—To start the working of a new filter bed, or one which has had its sand scraped, filtered water from the pure water well should be passed into it up through the filtering material at a slow rate, not exceeding 4 inches in depth per hour, so as not to disturb the sand while the full filtering depth is being attained. Thereafter raw water should be admitted slowly, and the resulting effluent run to waste until the increase of filtration head to a proper amount shows that the bacterial skin on and coating of the upper sand have been sufficiently formed. A bed thus filled will probably be at first not so compact as one filled from above, but this defect will disappear after a little time; the former is less likely than the latter to be fissured by the escape of imprisoned air.

(*h*) *Bacteriological Examination of Filtered Water.*—The ratio of the difference between the numbers of bacteria in the raw and in the filtered water to those in the former has been called the "bacterial efficiency" of the filter. As the number of germs in the filtered water includes those produced during filtration, "the bacterial efficiency" does not indicate separately the number destroyed which was originally in the raw water, which reduction has been described as the "bacterial purification" due to the filter. To determine this latter some special germ not naturally present, nor likely to develop, is added to the raw water, and the numbers of it detected in the raw and filtered water indicate the required "bacterial purification" or percentage of pathogenic germs removed by the filter. The final tests of efficiency are afforded by the case and death rates due to water-borne diseases of the population served. These results furnish statistics for future guidance, but are obtained too late to allow of immediate preventive measures being taken. Seeing how the conditions of each filter bed in the complete installation vary continuously, it is desirable to test, daily and separately, the effluent from each. Where this is not practicable, as many tests as possible should be carried out, especially at the season when water-borne diseases are usually most rife.

CHAPTER XXII.

SUPPLY WORKS.

256. Projects.

(*a*) *General Remarks.*—A water-supply project consists of works for the (1) collection (Art. 257), (2) purification (Art. 258), (3) conveyance (Art. 259), and (4) distribution (Art. 278) of water The parts of a project may comprise—

- The headworks (storage reservoir or river, etc., intake) ;
- The supply conduit, aqueduct, or main ;
- The purification works (including sedimentation, etc., basins, and filter beds) ;
- The pumping station for non-gravitation schemes ;
- The distribution system (service reservoirs and pipe reticulation).

The classes of the different kinds of schemes arranged in order of merit are : (1) Gravitation, (2) pumping to service reservoir, (3) pumping to elevated tanks or stand-pipes, and (4) direct pumping. The advantages of gravitation schemes are that they are the safest, most economical in operation (although perhaps dearest in construction), and least liable to deterioration.

In discriminating between various competing schemes the following should be taken into account :—(1) Practicability of future enlargement ; (2) quality of the supply, both at the present and hereafter ; (3) safety, or reliability ; (4) economy of supply ; (5) convenience and easy supervision ; and (6) the financial capacity of the town. The cheapest project is one furnishing naturally pure water (such as from springs) at a high elevation and near the town. The dearest is one where the source of supply is distant from the town, at a low elevation with respect to it, and requires expensive purification. In the case of the latter economy may be effected by limiting the purified supply to domestic purposes and furnishing the unpurified water for commercial and public non-potable requirements; the two supplies should not both be delivered to ordinary houses owing to the danger involved by possible mistaken usage of the inferior for the superior one.

(*b*) *Comparison of Cost of Scheme.*—As the feasibility of a project will depend upon its cost, that will first have to be considered. The following should be taken into account:

- (i) The capital or original cost of the works;
- (ii) The annual maintenance cost for operation and ordinary repairs;
- (iii) The cost of special repairs and renewals at intervals of several years;
- (iv) The sinking fund to cover the capital cost in a certain number of years at compound interest.

The cheapest scheme will be that for which the total of these items, after capitalising (ii) to (iv), will be the least. If, as should be the case, the works are thoroughly maintained, they will practically always possess their original capital value, and from this point of view a sinking fund is therefore unnecessary. From another it is required so that thereby may be paid off the loan whereby the works were probably financed, and the town may thus be in a position to incur a further one for the general extension of its water supply, which by that time will probably be necessary. As each generation should pay for the works constructed for its benefit, the term of a sinking fund may well be limited to thirty years, although sometimes when the capital cost of the scheme was very large a longer period may be justified; the longer the term of repayment, the greater the total cost to the community, but the less its annual incidence.

(*c*) *Depreciation of Parts of Scheme.*—In connection with renewals the life of the different parts of the scheme has to be estimated so as to arrive at the amount for depreciation which has to be provided to maintain them. This life varies greatly according to the liability of the parts to decay or become useless despite ordinary maintenance. The following are given as generally fair allowances for it:

Masonry and earthen dams—perennial;
Cross-drainage works (according to the velocity of flow and nature of foundations)—100 to 200 years;

Buildings—100 years;
Cast-iron pipes (according to the nature of the soil and water)—30 to 75 years;
Riveted pipes (according to the nature of the soil and water)—20 to 50 years;
Hydrants, valves, etc.—15 to 30 years;
Engines—15 to 25 years;
Boilers—12 to 20 years.

The shorter the life, the less the necessity for providing in the particular item for great expansion of the scheme as a whole, owing to increase of population and demands for consumption.

257. Sources of Supply.

(*a*) *Storage Reservoirs*—(i) *Site and Works.*—In respect to the dam and waste weir water supply reservoirs are similar to irrigation ones. If there is any danger of failure of an earthen dam, such as very steep slopes at the river crossing, a masonry dam should be constructed instead (Art. 70). In ordinary situations an earthen dam properly designed and constructed is, however, as safe as a masonry one, and is generally cheaper, especially if sound rock foundations for the latter are at great depth; it is also easier to raise the former when this becomes necessary to obtain more storage for an increased consumption. The outlet differs from an irrigation one, as it is necessary to draw water continuously from near the surface as the level of that falls in order to get the best potable supply. Further, all outlet pipes should have double control of their inlet valves to ensure safety and easier maintenance; for these reasons an outlet tower is preferable to a simple headwall. Where the whole of the supply has to be pumped from the reservoir, an outlet should, if practicable, be dispensed with, so as to avoid the possible danger to safety due to its construction.

Large towns can afford the expense of a long supply conduit due to a distant reservoir; small ones cannot bear this, and therefore storage for them will have to be arranged for in their neighbourhood, and thus the choice of sites for them is limited. The result will probably be that the rate of storage will be much higher than that of an irrigation work. However, as the quantity of water required for a town is comparatively little, even thus the cost of the reservoir may be proportionately only a small amount of that of an entire scheme which comprises cheaper storage, but a more expensive supply conduit; for both projects the charge for distribution works has to be added. Another consideration to be borne in mind in regard to locality is the elevation of the storage above the town. It will usually be cheaper somewhat to increase the distance between the two to secure a supply entirely by gravitation and without pumping, or one of which only a small part will have to be raised artificially to command high areas.

An advantage of storage schemes over most others is that in them the water supply is actually in sight, so that when a shortage appears likely to occur, greater economy in use can be instituted, or emergency measures taken to increase the area of the gathering ground by feed channels, if these are practicable.

(ii) *Quantity of Storage.*—In Article 248 (*a*) the necessity for large storage capacity has been noted. In addition to the consumption by the town, compensation water may have to be provided for prior interests affected by the abstraction of water by the reservoir and in accordance with local rules. In England notices for compensation claims have to be served to owners of water-rights within 20 miles downstream of the place where it is proposed to abstract water. There from one-third to one-fourth the total discharge is due as compensation to the stream. This can most simply be given by means of an independent subsidiary reservoir having a proportionate drainage area and the required storage capacity, and by placing it under the control of the owners of the water-rights. It may be said generally that if the reservoir can be filled entirely by storm flow not previously utilised, all that can fairly be demanded for the satisfaction of such interests is the passage through the reservoir of the normal fair-weather discharge. Where extra expense has been incurred in getting a pure or high-level supply it may be possible to construct a subsidiary storage for compensation purposes at a less expensive site.

In order to reduce the loss from evaporation the basin of the reservoir should be deep, for which purpose on each bank its cross-sections should be concave, and not convex. This will increase the potability of the storage (Art. 249 (*j*)) by lessening the amount of bottom water which should not be drawn upon, and the extent of the marginal area laid dry as the reservoir surface falls, which area will probably allow vegetation to grow profusely, and this, when it is subsequently submerged and dies, may pollute the water.

(iii) *Quality of Storage.*—The quality of the stored water depends upon the number of human beings and animals, and the extent of cultivation in the catchment; the more free the area is of these, the purer will be the contents of the reservoir. A storage should not be constructed immediately downstream of a large population unless the drainage from the inhabited area can be diverted from it, or intercepted and utilised for irrigation well above its high-flood level (Art. 251 (*a*) (ii)); the same treatment, if practicable, should be adopted for more distant occupied areas. Legal powers should be obtained when the project is decided on so as to prevent the increase of contamination in and to conserve the sanitation of the catchment (Art. 251 (*a*)). During the construction of the works every precaution must be taken to prevent the fouling of the future basin by the workpeople. In some cases the bed of the reservoir is stripped of surface soil, as such contains the largest amount of organic matter; that decreases rapidly with the depth from the surface. If the total storage can be arranged to be given by two or more reservoirs in connection with the same supply main, it may be possible to work them alternately, and to allow the bed of the one first drawn on to exhaustion to dry and be purified by desiccation, which can be hastened by ploughing up the basin. The water for consumption should be drawn off from near the surface, where it is most free from turbidity and is of the highest potability. The water at the bottom of the reservoir should not be thus utilised, and, if practicable (as is the case where there is more than one reservoir), should be run to waste. The quantity thus rejected will depend upon the condition of the storage, and may in bad instances amount to a quarter of the whole. Reservoir waters are generally the best, as their quality is improved by sedimentation and storage, and they most easily can be conserved sanitarily.

Hilly drainage areas furnish the purest natural supply, but peat-covered areas discolour the water. Of particular geological formations igneous rocks yield the purest and softest supply. Limestone should be avoided on account of the hardness of the water from it and the possibility of its fissures leading water away underground. In England the supply from the New Red Sandstone is liable to spontaneous contamination if stored in uncovered reservoirs.

(*b*) *Lakes.*—If a lake has a high elevation and a sanitary catchment, it may be able to furnish a good gravitation supply. The intake works may consist of a conduit or tunnel; they should be situated remote from the infall of large streams, which may bring down undesirable sediment, and at some depth, so that the action of the wind will not stir up the bottom deposit. A lake to be utilised for water supply will generally be in the principal valley, and owing to its low elevation a pumping scheme will usually be necessary. That valley is likely to be populated and highly cultivated, so that further sanitary precautions have to be taken in locating the intake works; these will consist in placing the inlets where they will not admit any water contaminated by fresh sewerage, and maintaining very careful observations of the quality of the water drawn upon. If the contamination of the supply increases, the intake will have to be extended well beyond the source of pollution. Where a natural lake has not a sufficiently large available capacity, its storage can usually be enlarged as required by a slight increase to its depth, involving, as a rule, comparatively inexpensive works.

(*c*) *River Intakes.*—These are generally inferior to storage schemes, as a river has an irregularly fluctuating supply, and is liable to be polluted by storm water derived from the washing of the surface of the catchment, and not purified by sedimentation and storage; schemes from rivers will thus generally require artificial basins to make good defects due to the non-existence of such natural processes. The higher up the river the intake is placed, the purer is likely to be the supply, but the quantity will probably decrease and be available at more fluctuating levels. If practicable, a gravitation scheme should be aimed at, but if this is not attainable, pumping will be necessary. As in the case of a lake intake, great care is necessary to locate a river intake where the water will be free from sewage contamination; also near the coast, that it is well above tidal influence, which may induce saline contamination and may make the supply brackish. To lessen the deposit of silt and detritus at its site the intake should be on the concave side of the stream, or on a straight reach, and its sill should be some height above the bed. To prevent the admission of floating matter, the sill should be some depth below the low-level surface of the stream. The actual inlet is usually a well or lined passage (Fig. 138), into which the water enters by openings protected by gratings so as to shut off floating *débris*, and having a large area so as to reduce the velocity of inflow. From this passage the water passes into a chamber or a tunnel through inlet pipes, which may have at their heads floating pipes to admit only the clear upper water. Thence the supply is led by pipes, having their mouths protected by screens of fine mesh, to the pump shaft, and in this the pumps have to be placed at a level to secure sufficient supply at all times; the shaft has to be constructed water-tight and with its top raised well above high-flood level. The best form of intake (Fig. 139) resembles the outlet tower

FIG. 138

ORDINARY RIVER INTAKE

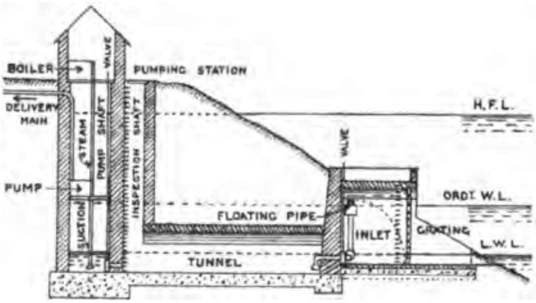
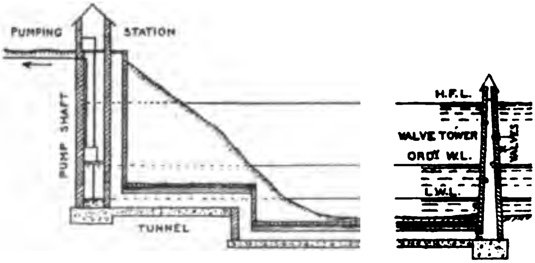


FIG. 139

RIVER INTAKE TOWER



of a storage reservoir, but is built in the deep bed of the river, and is furnished with draw-off pipes and valves at different levels, and the water is led from it in a tunnel to the pump shaft. Being an expensive arrangement, it is usually adopted only in a large scheme.

(*d*) *Underground Water.*—Water which has penetrated the ground tends to flow subterraneously towards the surface drainage lines some distance (depending upon the nature of the subsoils) downstream of its place of origin, or entirely underground to its final outlet. The more dense the subsoil, the slower will be the movement, and the smaller the quantity which can be intercepted. Even in open formations the rate of travel is much less than that of surface streams, as the frictional resistance to flow to be overcome is very considerable. It is only where continuous fissures exist, as in the dolomite formation, that there are underground streams with a defined flow. The danger attendant on these is that if the supply is contaminated in its course, it will not be purified by subsoil filtration, but may continue polluted for a great distance.

Before attempting to utilise underground water for supply, extensive geological examination of the area concerned is necessary, and it will be advisable to assist in making this to sink trial shafts along the probable line of flow to determine the subsoil hydraulic gradient, as on this the rate of travel depends. Dense rocks, such as granite, furnish practically no supply; fissured rocks, such as limestone, dolomite, trap, and sandstone, may afford good supplies if their fissures are continuous; porous gravel, sand, and chalk formations, especially when resting on impermeable strata, give the greatest amount of yield. In all cases the quantity which can be tapped depends upon the area of the formation, the character and the amount of the rainfall, and the surface flatness, the depth, and the porosity of the overlying strata. Infiltration of sea water in coastal areas is purposely excluded for such, if it occurs to any extent, will render the supply non-potable.

Underground water in concentrated flow can be tapped by means of galleries, which are usually open excavations of narrow width sufficient for constructional purposes, and these are subsequently roofed over, are lined on the downstream side by impermeable walling, and are provided with manhole shafts for inspection. If the ingress of sand is feared, that can be prevented by constructing a continuous porous filter on the upstream side. Galleries are usually best situated near streams, as there the underground catchment is likely to be the most extensive, and the low elevation will induce greater flow. Instead of depending entirely upon underground catchments, galleries are often constructed along the margins of streams (from which principally they then derive their supply, and not from subsoil flow), and at a distance of not less than 50 feet from the bank, so as to secure sufficient natural filtration; an excessive rate of draught involves certain deterioration of the supply. The quantity of flow will depend upon the nature of the subsoil and of the river bed and discharge. Streams which have a turbid flow soon choke galleries, and those which have an impermeable bottom, whether of clay or deep silt, furnish the least supply, while those the channels of which are scoured out by floods and are subsequently filled with sand, or have fissured rocky and clear beds, give the most supply.

Galleries have generally the advantage that by extending them the amount of water tapped can be increased; an objection to riverside ones is that the rate of percolation into them varies directly with the amount of river flow, and is thus least in the dry season when supply is most needed. The probable minimum rate of percolation into a gallery should be tested by sinking several trial pits on the line proposed for it and pumping them out at the close of the dry season.

In certain cases galleries have been constructed across river beds; such works may furnish the most abundant supply. Unless, however, the depth at which they are driven is considerable, the water, although clarified, may not be purified from bacterial infection.

Occasionally streams having deep sandy beds disappear into them and have no surface flow. The water in them may, however, be interceptible by the construction of submerged water-tight dams of puddle or masonry across their course (Art. 160 (*e*)).

Unless a gallery is formed above a sudden and considerable fall in the stream bed, or otherwise well above the town, the supply derived from it will have to be pumped from a pump shaft at the downstream end, and cannot be utilised by gravitation.

(*e*) *Springs*—(i) *General Remarks.*—Springs are the overflows of water which has previously found its way from the surface by percolation into the subsoil. The larger the underground catchment, other conditions being the same, the more permanent will be the spring and the more regular its flow; deep-seated springs are thus the most reliable in regard to the permanence and quantity, and they are usually the best in respect to the quality of the supply which they furnish. The quantity of supply depends upon the surface slopes, the nature of the surface and subsoils, and the character and amount of the rainfall; it will be at a maximum when the slopes are flat, the surface and subsoil absorbent, and the rainfall moderate in intensity and well distributed throughout the year. It will be at a minimum when the ground has steep impermeable slopes, the subsoil is dense, and the rainfall descends in violent storms, of which much at once runs off, and when these occur at considerable intervals.

As a spring is an overflow, it follows that usually it should not have its discharge increased artificially, for the effect of this in such cases will lead but to a temporary improvement, lasting only as long as it takes to run off the feeding underground reservoir to a lower level, and that reservoir, being thus reduced in size, will have diminished power to maintain a regular flow. Only when subsoil water continues its subterranean course below or to the side of the spring, and naturally escapes being drawn into that, is it advisable to lead it artificially to the spring either by deepening or by means of lateral adits or galleries.

The sufficiency of a spring should be gauged by means of a weir notch; a triangular one is preferable, as the coefficient of its discharge remains sensibly constant for all depths of flow over it (Art. 53 (*h*)). The gauging should be undertaken at the end of a period of prolonged drought, and to provide for contingencies the minimum discharge should considerably exceed the anticipated rate of consumption. The best natural condition is when there are two or more separate springs near each other, as then, when necessary, they can have their flow combined as required for the water-supply scheme. Care should be taken to see that the gathering ground of the springs is a sanitary one.

Springs may be classified as Outcrop, Artesian, or Overflow.

(ii) *Outcrop Springs.*—When rain falls on a pervious stratum a portion of it percolates into that until it meets a fissure, or is arrested by an impervious substratum; where either of these leads out to the natural surface a spring may be produced at the outcrop (Fig. 140). When there are several small springs close to each other, each may be separately enclosed, and the effluent from it led into a supply main common to all, or adits may be run on each side from the central spring parallel to the outcrop to tap the discharge of the side ones. The collecting basin formed round a spring is usually built like a well, but is roofed over to exclude the light, and thus to prevent the growth of vegetable organisms. In addition to the conduit pipe, which should be controlled at its head by a valve, there should lead out of it an overflow pipe, and also an unwatering or scour pipe at low level to enable the basin to be drained for repairs, etc.; a weir-gauging chamber should be constructed if it is determined to obtain discharge statistics. If the water brings in sand the basin should be enlarged and deepened so that the sand may settle below the indraw of the effluent pipe, and may be scoured out at intervals through the scour pipe.

FIG. 140

OUTCROP SPRING

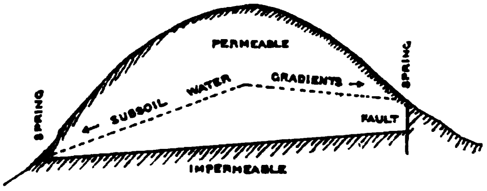
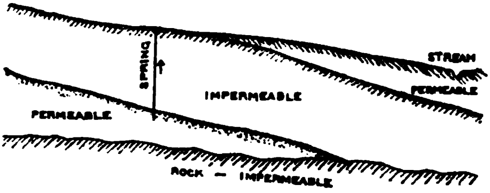


FIG. 141

ARTESIAN SPRING



(iii) *Artesian Springs.*—When a pervious stratum with an elevated surface outcrop at its head is surrounded by impervious strata (Fig. 141), the combination virtually becomes a large natural pipe, in which the water has a pressure head due to the elevation of its inlet; if this is sufficient to bring it to the surface, the spring is a true artesian one; if not enough for this, the spring is a sub-artesian one. The water which percolates in at its head is confined by the impermeable strata until it finds a way of escape; if this is afforded by a vertical fissure or a fault, or if the overlying strata can be burst through by the pressure, the water will rise to the surface, and there issue as a spring. The natural passage may be improved by boring, or may be replaced by a well shaft, and this should be treated as described under (ii). Artesian springs of great depth may furnish water with an objectionably high temperature for drinking purposes.

(iv) *Overflow Springs.*—These are the natural surface overflows of subsoil water in a porous formation (right-hand side of Fig. 141), the lower portion of which is saturated so that the percolation coming to it cannot otherwise be carried away. Such overflows can be collected and dealt with by wells or galleries.

(*f*) *Wells and Boreholes*—(i) *General Remarks.*—Wells and boreholes are artificial arrangements for tapping subsoil water where there are no natural springs to bring it to the surface, or they may be constructed so as to improve such springs. Usually, as compared with each other, wells are shallow and boreholes deep. For the proper location of their sites careful geological examination is necessary by test borings, etc.; precautions should be taken to secure sanitary gathering grounds, and surface water which is likely to be contaminated by drainage should be excluded by means of water-tight casings. Casings are also required when the strata passed through are soft, and by falling in would choke the shaft, or where the subsoils are pervious and would allow water obtained from lower levels to escape through them; in both instances the linings should be continued for some distance into sound and water-tight adjacent strata.

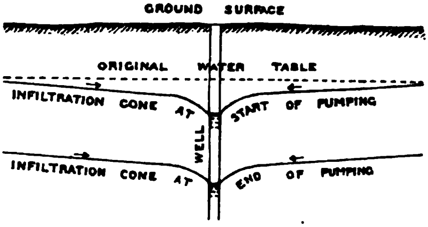
Wells and boreholes should not be drawn upon to an extent greater than the annual infiltration, nor so as to induce rapid extraction of the saturation of the surface should that be contaminated; excessive draught invariably leads to deterioration of the quality of the supply. If pumping permanently lowers the water level in them to an undesirable extent, additional shafts, or bores, should be sunk to increase the area of the subterranean catchment; the possibility of thus being able to increase the supply gradually as may be required is a great advantage of such works. With the same end in view wells may be deepened by excavation (if the geological conditions justify this), or, more cheaply, by having boreholes drilled in their beds, or adits may be driven horizontally from them. Boreholes can be deepened, and some have been rendered more efficient by exploding dynamite, etc., charges at their bottom so as to open out fissures in the rock there. The deeper the shaft, other things being equal, the larger and more permanent should be the supply. Where a great depth is necessary, the expense of constructing a well may be prohibitive, and then recourse should be had to one or more boreholes. Large wells have the advantages over small ones of increased storage capacity, thus allowing pumping to be carried on at variable rates; of giving more space for the erection of pumping machinery, and of having that installed at only one site, thus obviating long water-tight suction pipes from connected small wells; of reducing loss of head by friction; and of preventing the ingress of sand by their low rate of inflow.

Wells should be covered to exclude light, which encourages animal and vegetable growth, and to protect them from exterior pollution. In sinking boreholes care should be taken to drive them vertically; they may be bored by a jumper, or drilled; the latter operation enables cores to be obtained of the strata passed through, and these give valuable geological information. Drilling is generally effected by means of a crown set with boring diamonds, and is thus expensive; more recently the "shot drill," in which chilled steel shot are fed under a boring bit, has been used, and has proved economical, and permitted larger bores to be made.

(ii) *Infiltration Cone.*[1]—Fig. 142 is a diagrammatic section of the infiltration cone, or volume of subsoil draining into a shaft when the water surface in that is lowered by pumping. Since the area of the inflowing water decreases, and its amount increases, as the shaft is approached, so is its velocity increased, and therefore is its hydraulic gradient steepened. There are formulæ giving the rate of flow from an infiltration cone of theoretical uniform geological constitution, but to determine the coefficient of discharge due to the porosity of the

FIG. 142

INFILTRATION CONE


GROUND SURFACE
ORIGINAL WATER TABLE
INFILTRATION CONE AT START OF PUMPING
WELL
INFILTRATION CONE AT END OF PUMPING

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[1] Also called "cone of depression," or "cone of abstraction," and its base in America the "circle of influence."

actual subsoils it is necessary to make practical observations. The rate of discharge is not greatly affected by changes in the base area of the infiltration cone, the radius of which extends to where there is no sensible flow, and the hydraulic gradient is practically parallel to and coincident with the natural subsoil water table, or surface of underground saturation; nor is the discharge much influenced by the diameter of the shaft. It is chiefly governed by the porosity of the subsoil, and is directly proportional to the depth to which pumping lowers the water surface in the shaft; thus, if that depth is doubled, so will be the rate of inflow. It is therefore desirable to tap the subsoil water table at a high level with respect to the ground surface, and this will usually be practicable in low ground and near streams.

Where several shafts are sunk to increase the supply, care should be taken to space them so that each drains its infiltration cone independently of those of its neighbours; if placed nearer together, the total discharge will be diminished by the extent the areas of the cones overlap each other.

Thus if a new shaft is sunk with its infiltration cone including an old shaft in its area, the draw-off from the former may diminish that from the latter in proportion to their relative depths, and thus the former, if sunk deep enough, may drain the latter dry; many failures of old wells thus take place. The English law does not give any protection to the owner of the old shaft unless he can legally prove that the subsoil water between the two flows in a defined channel—this it is practically impossible for him to establish. The Transvaal law, as recently enacted, prescribes in the reverse way that the owner of the new shaft has to prove legally that there is no defined channel connecting it with the old shaft, and this usually is equally impossible of proof. The effect of the latter law is most beneficial, as it gives security of tenure by protecting old users from exploitation by new users. Under the former law they have no remedy but to deepen their shafts, and thus ruinous competition may take place between the new and old users. Development by the utilisation of subsoil water can be secured under the Transvaal law by prescribing legally the extent of infiltration area to which the old user is entitled; this should take into account the depth of his shaft and the porosity of the strata surrounding it.

The most favourable situation for a shaft is one where it intercepts a long and large fissure, as that throughout its course will drain its marginal area just as a succession of shafts would do. The discharge admitted by such a fissure cannot be calculated by theory, but must be ascertained by experiment. As the resistance to flow in it varies approximately as the square of the velocity instead of as the first power (which occurs when the subsoil is uniformly porous) the yield of the shaft by lowering its water surface will not be increased at the same rate in the first as in the second case.

(iii) *Pumping Tests.*—To establish the sufficiency of a shaft, pumping tests should be instituted at the end of a long period of drought; the amount pumped should be carefully measured over a gauging notch, and the rate at which the water level in the shaft is lowered should be observed and recorded. If this is rapid, it indicates that the infiltration cone above it is small and quickly drained, and cannot be depended upon for a permanent supply; if it is slow, it shows that the cone is either large or receives a considerable amount of fresh percolation to replace the original saturation, and that the supply is likely to last long. The tests should be long continued so as to avoid an over-estimate of the permanent yield due to merely temporary surface infiltration. The amount of draw-off should be increased as necessary so as to determine the level to which the water in the shaft can be lowered, so that the rate of outflow may not exceed that of inflow, and thus to indicate the amount of steady yield which may be calculated upon from the shaft. As a precaution against failure of supply, the actual draw-off contemplated should be less than this amount.

(iv) *Pumping Systems.*—These may be classified thus:

(I) Pumping to a large elevated service reservoir;
(II) Pumping to a small elevated tank or stand pipe;
(III) Direct pumping.

In the case of (I) the larger the service reservoir the more does the system approximate to a gravity supply. The service reservoir increases the capital cost of the scheme, but against this may be offsetted economy in the size of the rising main, which may be designed ultimately to give the whole day's supply in eight hours, thus allowing the plant to be worked for the maximum period of a shift and at a constant rate. It also allows time to be secured for the repair of the pumps.

For (II) the capacity of the tank, etc., should be at least equal to one hour's fire consumption. It may be more economical and convenient than (I) should the site for a large elevated service reservoir be at some distance from the pumping station.

Of the three systems (III) is the least desirable (however, see end of Art. 266), but has the advantage of flexibility in working, as the pressure may be regulated as necessary, being raised only when required by unusual circumstances, such as the extinction of a fire, and being otherwise maintained low.

258. Filters.

(*a*) *General Remarks.*—The location of the filters with respect to the whole project has been discussed in Article 255 (*b*). The different compartments of a filter should be arranged as compactly as possible and conveniently for their working with especial reference to the washing and storage of their sand. The water in them should have a continuous flow from the sedimentation, etc., chambers upstream to the pure-water reservoir downstream, from which the treated effluent passes to the town. The dimensions of the compartments depend upon the nature of the ground available and their number and area, also on the settled rate of filtration which is governed by the nature of the water, and is determined upon after experiment or investigation. In addition to the number actually in use should be one, or (when the filter beds exceed eight in number) two, reserve compartments to permit of cleaning and refilling being carried out without reducing the total filtration area in operation. In England the average area of filter beds in continuous working is 0·81 of the total area of the beds.

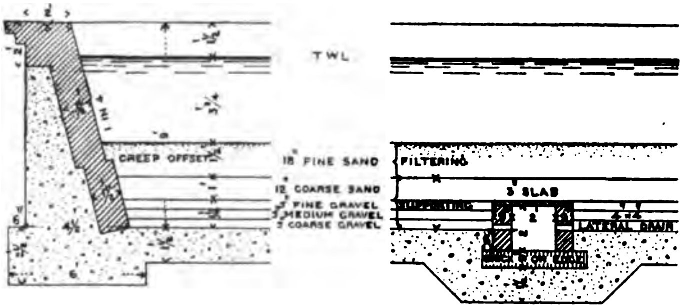
(*b*) *Slow Sand Filters.*—These are generally constructed in rectangular compartments, usually 200 feet × 200 feet to 250 feet × 200 feet, but have also been designed as sectors radiating from a common centre; the area considered may be that at half the original depth of the filtering sand. The sides of uncovered filters may be sloped, but those of covered filters are formed by vertical walls; for the former the bounding slopes must be raised so as to give a free-board of from 6 inches to 1 foot above the full-supply surface of the water on the filter bed, while for the latter the walls must be built sufficiently high to give headway for working the filter from the inside.

The filtrating sand is supported (Fig. 143) by coarse sand and layers of gravel, graduated from fine to coarse, of minimum thickness sufficient to prevent any material being carried away by the underlying drains; these layers have no sensible purifying action on the water. A main drain runs axially down the centre of the length of the compartment, should gradually increase, say, from 1 foot × 1 foot to 2 feet × 2 feet (so as to secure an uniform fall of pressure in it), and should have its head about level with the top of the laterals so as to reduce the amount of gravel filling. The water is led into it by laterals, usually of 4 to 8 inch round tiles, or made as brick drains, all with open joints at intervals of from 8 to 12 feet, and covered by a layer of coarse gravel at least 6 inches thick; or the whole floor may be laid as a continuous series of brick drains. The last-named system gives the most

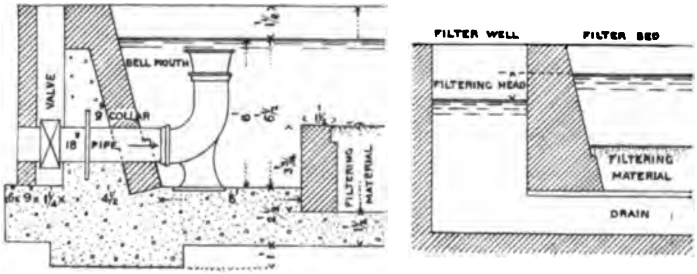
FIG. 143

FILTER BED

SECTION AT WALL   SECTN THROUGH MAIN DRAIN



SECTION AT INLET   DIAGRAM OF FILTRATION HEAD



uniform and slow-moving drainage, and thus produces the least tendency to rupture the bacterial skin, but it increases the depth of the filter by a few inches, and thus its cost. The vertical rate of filtration through the sand is least at the head and greatest at the outfall of the laterals; to equalise that rate as much as possible, the laterals should therefore be numerous, short, and of large area, so that the decrease of pressure in them may be as uniform as practicable. In order to attain these conditions the filter should be oblong rather than rectangular, or the laterals should discharge at right angles into larger collecting drains at intervals, and these at right angles into the main drain.

It is essential to preserve the continuity of the bacterial skin, for if defined channels are formed in it the raw water will pass unpurified through them. To prevent such creep of water down the side walls they may be built with an offset from the face as shown in the Figure; the drains should be stopped short of the side walls and internal piers, and should have their heads blocked by fine sand carried up to the filtering bed proper; ventilating pipes passing up from the drains through the filter should be similarly lined externally. Some consider these pipes unnecessary if the filter is started by being filled slowly from the bottom, as it should be, but even then they are useful in preventing any blowing up of the sand and consequent rupture of the bacterial skin. Care should be taken to found all walls and piers securely so that there may not be any excess settlement at them which would tend to form a crack. The bottom and sides of the filter should be water-tight so as to exclude external percolation; to obviate this its bed should preferably be placed above subsoil water level.

Filters are often roofed over by series of masonry or concrete arches and vaults, supported by piers, and covered by earthwork, principally to prevent their being frozen over, but also to keep the water free from dust, growth of algæ, etc., from becoming unduly warm, and from breeding mosquitoes. The cost of such protection is about a third of the total cost of the filter.

Each filter bed should be provided with inlet and outlet pipes, and also wash-out, overflow, and by-pass pipes, all furnished with valves, and regulating apparatus fixed in a chamber or chambers downstream of it so that its action can be separately controlled. After this the water should be passed into a pure-water reservoir with its full-supply level a little below that of the regulating chamber, and with a minimum capacity of about three hours' consumption, so that the rate of filtration may not have to be varied much, and so that the fluctuations in pumping will not affect it.

Slow sand filters are best adapted to dealing with comparatively clean water; they are most regular and simple in their action, they remove turbidity and most of the bacteria, and effect a little chemical purification. Although some bacteria pass through them, they are the best type known.

(*c*) *Intermittent Filters.*—In these the filter beds are drained dry once a day, and are allowed to aerate, after which they are again filled and the filtration resumed; the amount of water filtered is thus reduced by the time the filters are dry. The aeration is beneficial to the nitrification of organic matter in a water originally deficient in oxygen, and leads to a greater destruction of bacteria both in the filter and in the under drains. As little surface film is formed, the bed requires scraping less frequently. The working of the intermittent is more irregular, slow, and difficult than that of the continuous system, and thus the former is not often installed.

(*d*) *Mechanical Filters.*—This kind of filter has been adopted extensively in America, where different designs for it have been patented. The body of the filter consists of a cylindrical wooden or steel tank, in which from 2 to 4 feet of filtering sand is placed on a layer of gravel. Water is admitted to the surface of the sand through a central vertical pipe, and after descending by gravity through the filter material, enters collecting pipes at the base and is passed out for consumption. The rate of filtration is extremely rapid, and to ensure its efficiency dependence has to be placed on prior coagulation by sulphate of alumina or common alum (the double sulphate of alumina and potash) in a coagulating basin to remove turbidity and bacteria; it would seem that the filter itself has but a small share in the purifying process, except to strain off bacteria in the scum formed on top of the sand. It rapidly gets clogged, and has thus frequently to be cleansed, usually once a day. In one type the cleansing is assisted by rakes deeply penetrating the sand and made to revolve through it by machinery; in another type there are no mechanical agitators, but the sand is loosened by air forced through it from the bed. The actual cleansing is effected by water forced upwards through the sand for about a quarter of an hour, and passing out over the top of the tank. Mechanical filtration is adapted to the treatment of water heavily charged with fine silt, much iron, and decaying vegetable matters. Its advantages are:

- Reduction of the area required for the installation;
- Reduction of the capital cost of the installation;
- Cleanliness of operation;
- Removal of practically all turbidity and nearly all of the bacteria.

Its disadvantages are:

- Increased cost of operation;
- The necessity for skilled operators;
- The necessity for carefully regulating the coagulant to the character of the water dealt with and for large settling basins;
- The use for washing of a relatively large amount of water (about 5 per cent. of the filtered supply);
- Irregularity of bacterial purification if the surface film is ruptured (this can be detected if a continuous pressure gauge record is kept, and the danger can then be avoided).

The last-mentioned advantage and disadvantage are the most important. The system seems best adapted to turbid water not highly polluted, and least suitable for clear water much contaminated.

259. Conduits and Mains.

(*a*) *The Supply Line.*—This forms the communication between the source of supply and the works at the head of the town distribution system. Its length will probably be at a maximum when that source is a storage reservoir, and at a minimum when it is a river from which water is pumped. It must be made as secure as possible, and at its downstream end must be storage capacity to tide over interruptions to its flow either by accident or by maintenance operations. Its discharging capacity must be sufficient not only for present requirements, but for probable future expansion for a period depending upon the life of its works; that period will thus be comparatively short when the works are of a temporary character, and comparatively long when they are of a permanent nature. The capacity must also be in excess of the rate of average daily consumption so as to meet extra demands, including those arising from a temporary stoppage of the supply line when the tail storage has been drawn upon and has again to be replenished.

There are several kinds of supply line of two main descriptions, viz.:

A. Flowing with free surface.

Open channels and masonry aqueducts.

B. Flowing under pressure.

Mains of different materials.

The alignment of the supply line has to be in accordance with its nature, but consistent with this should be as short as possible, so as to lessen the time of transit, and, in the case of A, the loss in transit. The alignment is also, of course, dependent upon the cost, and the generally best one has to be determined by the survey and estimation of competing routes.

(*b*) *Open Channels.*—These are much the same as irrigation canals, and the alignment of the two is similar. If practicable, that of the open channels should be suitable for utilisation in an aqueduct scheme, if such improvement is likely to be made in the future. If the head available is sufficient, the velocity allowed should be as great as the strata met with will stand, so as to reduce the cross-section. Heavy embankments and deep cuttings should be avoided, as also should be porous formations and those which involve any risk of failure. Land drainage should be excluded by means of double banks. Cross-drainages must not be allowed to enter the channel, but should be passed under or over it. On account of the comparatively small amount of its discharge, the channel can usually be passed across the cross-drainages in troughs or pipes. Escapes for passing off flood water should be provided, especially upstream of works, the safety of which is of great importance, and these should also be built for silt clearance purposes.

The advantages of an open channel are:

- Its cheapness—this is the chief thing in its favour;
- Its large discharging capacity—a slight enlargement of the cross-section theoretically required will much increase the discharge;
- Its permanence owing to the long life of the channel and the works thereon;
- Its small loss of head.

The disadvantages of an open channel are:

- Its liability to sanitary pollution—this is its chief defect, to guard against which it should be well fenced and carefully patrolled;
- Its liability to vegetable contamination by marginal plant growth;
- Its long length, increasing the time of transit;
- Its greater loss in transit owing to percolation, absorption, and evaporation;
- Its greater cost of ordinary maintenance.

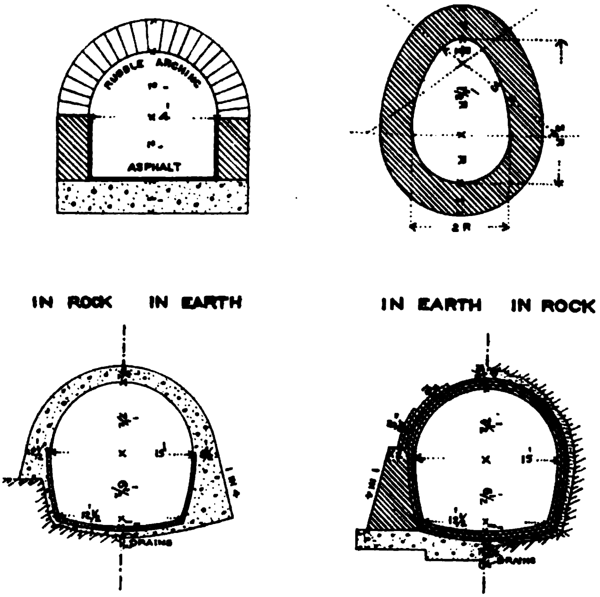
The disadvantages generally outweigh the advantages, and it is therefore seldom in ordinary cases that an open channel is made. It may be adopted for a very large scheme with a long supply line in thinly populated and little cultivated country, when the consequent saving will be great; or for a very small one, where every economy has to be practised.

(*c*) *Masonry Aqueducts*.—These are sanitarily superior to open channels, as they are protected from external contamination. They are best adapted for schemes which have to supply a large volume of water and to country with gentle slopes. They are generally cheaper than pipe schemes if they have a cross-sectional area of not less than 10 square feet, but may be dearer than them if of an area smaller than that; they are more expensive than open channels. To reduce their cost their alignment should be as direct as practicable. In construction they are usually of masonry, but they may be of ordinary gauged cement or reinforced concrete, and they are generally built in cut and cover, and with brick linings where necessary and brick arching. The arch head should be covered 3 feet deep by earth filling or embankment to secure coolness and also protection from frost. The velocity through them should be as high as their material will permit—up to

10 feet a second when sound, hard stone is used—and the gradient practicable allows; it should not be less than 3 feet a second, so as to prevent deposits and growths. Theoretically, the best cross-section is a circular one, as that has the greatest hydraulic mean radius, but in practice others are adopted (Fig. 144). Rectangular angles are objectionable, as allowing deposits to collect, and deep inverts are costly if they lead to constructional difficulties in water-bearing strata; the internal

FIG. 144

MASONRY AQUEDUCT SECTIONS



height and width should be sufficient to permit of easy construction and inspection. The cross-drainage works are similar to those of open channels; long and high arched crossings should be avoided; troughs or pipes may be substituted for the masonry cross-section at important crossings. High embankments are not advisable, but where they have to be made, the aqueduct should be given a wide base and the earth foundation should be well consolidated and drained. Deep cuttings are also not desirable; in fact, the aqueduct is best if a surface one conforming to the levels of the natural ground. Tunnels are excavated when high ridges are met with, so as to save a long length of aqueduct on a surface falling contour. If they are in sound rock they need not be lined, but should be if the strata are liable to disintegrate. The smooth lining of a tunnel increases its discharge (end of Art. 146).

The advantages of a masonry aqueduct are:

Its suitability from a sanitary point of view;
Its durability and safety from a constructional point of view;
Its cheapness compared with a pipe main for fairly large supplies;
Its small cost of maintenance;
Its small loss of head.

The disadvantages of a masonry aqueduct are:

Its cost and difficulty of construction for small supplies;
Its inability to withstand great internal pressure.

On account of its advantages a masonry aqueduct is best suited to a large supply scheme, especially if it crosses thickly populated and much cultivated country.

(*d*) *Pipe Mains.*—These mains may be of cast iron, riveted steel, or wooden staves. For small schemes where economy is essential, concrete pipes, either moulded in lengths or formed continuously *in situ* on movable cores, may be used. To reduce their original cost only the lower half may be made at first, the upper half being added subsequently if desired. Glazed earthenware half or whole pipes may be laid in similar conditions; the objection to them is their numerous joints, causing friction and waste.

The alignment of the main should be as direct as the nature of the ground will allow (so as to reduce its cost) and the pressures involved will permit. The pressure should be as low as practicable; to reduce it the main should have a free outlet, for if that is closed the line will then be subject throughout to the head due to its inlet (Fig. 145). Further, to reduce pressure, intermediate reservoirs, known as equalising, balancing, or break pressure, may be constructed so as to divide the whole line into independent sections; or pressure regulating devices (para. (*e*) below) may be installed and pressure relief valves (Art. 265 (*d*)) fixed at intervals. The main should, if practicable, be laid near the surface of the ground, with sufficient earth cover, say, 3 feet, as a minimum, to protect it from damage and freezing, and to keep it cool. It is best that it should have a continuous fall, but where this cannot be arranged, there should be an air valve at each summit and a scouring valve at each depression; rises above the hydraulic gradient should be avoided. Cross-drainage works will usually take the form of pipe aqueducts or inverted siphons. High ridges above the hydraulic gradient can be crossed by deep excavation or by tunnels in extreme cases, long depressions by inverted siphons and short ones by pipe aqueducts. The pipes must be securely founded and packed at the bed and sides (Art. **263** (*b*)).

The advantages of a pipe main are:

Its excellence from a sanitary point of view;
Its safety and capability of being quickly laid and repaired;
Its power of withstanding a large amount of pressure;
Its quick delivery of supply with practically no loss in transit;
Its small cost of ordinary maintenance.

The disadvantages of a pipe main are:

Its heavy capital cost;
Its comparatively short life, necessitating renewals at intervals;
Its liability to be choked by incrustations (these may be removed by scraping);
Its comparatively large loss of head.

The advantages so much outweigh the disadvantages that for most schemes of ordinary size pipe mains are preferred and adopted. Ancient water-supply works were much handicapped because iron pipes were not available for them. In Rome lead pipes were common, and in the East earthenware pipes were used, but with them only low pressures could be met, and old schemes are therefore usually gravitation ones following the surface of the country.

(*e*) *Works on Supply Line.*—In addition to those briefly noted above the following are the principal works to be provided.

At the intake should be arrangements for admitting, regulating, and measuring the discharge, and provision made by screens and gratings against the entry of *débris*, etc. The admission may be effected by valves or sluices, the regulation by an automatic overflow, and the measuring by a gauging run, notch weir, Venturi meter, or other device.

At the downstream outlet end should be a tail reservoir of capacity sufficient to tide over the time which may be required to repair the supply line—fifteen days may be wanted for an open channel or aqueduct, while four days may be sufficient for a pipe main. This is generally a cheaper arrangement than making the conduit in duplicate, so that one branch may be closed and repaired while supply is being given by the other branch. When such duplication is designed, the two branches should have cross-connections at intervals so that each section thereof may be shut off and attended to independently of the others. If the supply conduit is likely to deliver turbid water, the tail reservoir should be sufficiently large to allow for subsidence to take place; to aid the natural rate of this, artificial sedimentation (Art. 252 (*b*)) and coagulation (Art. 253) should, if necessary, be effected. The tail reservoir must be kept at its full-supply level throughout the ordinary working of the system, so that it may have its full storage capacity available whenever the supply line has to be shut off. It should be protected from further rise by being furnished with an overflow, and it should be provided with an inlet and outlet so that its levels and discharge may be regulated.

When the supply line is very long, it may be advisable to have on its course intermediate reservoirs, the capacity of which may be additional to, or considered part of, that of the tail reservoir. Thus, when repairs are required it will be necessary to shut off only the section where they have to be carried out and the ones upstream of that; the supply can then be passed into the lower sections from the intermediate reservoir immediately downstream of that section, and when this is exhausted, by the others in downstream rotation, so that the tail reservoir itself will be drawn upon last.

The different sections of the supply conduit thus formed should be provided with shut-off arrangements and automatic overflows, or waste valves, in connection therewith. With the former may be combined scouring arrangements, so that advantage may thus be taken of the closure of a section then to clear those upstream of it by flushing them and allowing the water to run to waste. Intermediate overflows and scouring works should be provided as may be necessary. As their life is long, such reservoirs provide in the cheapest and most permanent manner against the interruption of supply, whereas the alternative duplication of a supply main or channel involves the construction of a second pipe line, or a second set of cross-drainage works, each of which will have a shorter life and necessitate a greater amount of maintenance.

260. Deterioration and Life of Pipes.

(*a*) *Internal Growths and Deposits.*—Pipes are liable to corrosion and to choking by deposits and growths internally, and to corrosion externally, so that in unfavourable conditions their discharging power may be considerably reduced, and they may have a comparatively short life.

Internal corrosion occurs chiefly with acid waters containing free carbonic acid, but may also happen with neutral waters; it usually starts at a pinhole, where the applied coating of the pipe is absent; chloride of sodium, even in small quantities, greatly aids the formation of tubercles. A tubercle, consisting mainly of oxide of iron (dissolved from the pipe) and some silica, lime, and organic matter, forms at the defective place, and may grow to a diameter of 1½ to 2 inches, and a thickness of ½ to 1 inch. Below the tubercle the pipe is corroded, and its metal made soft by the action described in Art. 254 (*c*). Tubercles not only diminish the cross-section of the pipe, but also increase its roughness, and from both causes lessen its discharge; their choking effect is greatest in small pipes, as in large pipes the fact that they do not continue to thicken prevents them from proportionately reducing the cross-section. The preventive to their formation is a good coating of the pipe and the filling of pinholes therein by painting them over with asphalt varnish; the remedy to be applied after their formation is scraping. They can be lessened by placing the filters near the source of supply. Some corrosion of even well-coated pipes is likely to take place in from ten to fifteen years, but properly tar-coated pipes have been known to keep bright and clean from twenty to thirty years.

Coatings of black slime occasionally occur, chiefly when the water is derived from a peaty storage, and generally are limited to the first 5 miles of the main. They are believed to be due to the action of vegetable organisms acting on salts of iron originally contained in the water, or produced by the attack of acids in solution on the metal of the pipe. The remedy is the neutralisation of the acid by rapid filtration through powdered limestone, and sometimes through simple sand filters.

Incrustations of carbonate of lime frequently result from hard waters containing an excess of that salt; such being smooth and regular may not diminish the discharge greatly. The best preventive is Clark's water-softening process (Art. 254 (*b*)), carried out before the water enters the main, and the best remedy is scraping.

Deposits may also collect at depressions in the pipe line and at dead ends; these may be due to silt, nodules of oxide or carbonate of manganese, or iron precipitated in water containing these metals, or to *débris* from incrustations. At the depressions they may form considerable obstructions to flow; they should be loosened by a rotatory brush, and should be discharged through scour pipes.

Soft water may thus produce tubercles and slime, while hard water may lead to incrustations and deposits. The formation of these causes loss of velocity, or increase in the head required; even for slight deterioration it has been recommended to allow 10 per cent. for the first and 20 per cent. for the second on the amounts calculated theoretically for new pipes. As a further precaution against choking by incrustation it is advisable not to lay pipes of less than 4 inches diameter.

(*b*) *External Corrosion.*—Salts, such as alkaline ones, which act on iron, and are contained in the natural soil, or in artificial refuse, such as slag, ashes, and cinders, will corrode the exterior of the pipe. This action will be retarded by the protective coating as long as it lasts, and might possibly be prevented in the case of large pipes by casings of inert earth, or by the substitution of reinforced for simple metallic mains.

Another serious form of corrosion, which is more likely to occur in the distribution system than in the supply main, may arise from the electrolysis due to return currents from single trolley electric railways, if these do not pass along the rails, but escape through the earth to pipe lines, and traverse them until attracted from them. It is where this happens, i.e. where the current leaves the pipe, and not where it enters it, that corrosive electrolytic action takes place; the amount of this depends upon the strength of the current and the nature of the salts in the soil. The remedy consists in preventing the escape of the current to the pipe either by the substitution of the double for the single trolley system, or by the provision of a good return conductor.

(c) *Life of Pipes.*—The life of cast-iron pipes and the time during which their discharge will not be greatly reduced depend chiefly upon the excellence, including the continuity, of their protective coating. Uncoated pipes may become badly tuberculated within ten years, but properly coated ones may remain unaffected for twenty or thirty years. Internal corrosion may not greatly impair the strength of a pipe, but may much lessen its discharging capacity, and both hard and soft water may lead to deterioration of different kinds. The prevention of this again depends greatly upon the coating, and when this has been properly applied, the pipes may remain practically unaffected for fifty years.

Steel pipe coated with asphalt has been found in perfect condition after thirty to forty years; in other cases it has corroded rapidly, and its life has been short compared with that of cast-iron pipes. For the New York water supply it was estimated the pipes would last for fifty years if they were cleaned and painted at intervals of about ten years.

Wooden pipes buried in the ground and kept full of water are likely to have a long life. Stave pipes have mostly been laid only recently, and have thus not been sufficiently tested, but some have lasted well during forty years. They are as durable as thick steel pipe, and much more so than thin steel pipe, which might be substituted for them. The steel bands round stave pipes will deteriorate more rapidly if buried in the ground than if they are in the open, when they can be cleaned and painted at intervals.

Concrete and glazed earthenware pipes, if preserved from breakage, should have long lives; they are not liable to tubercle formation, but may be affected by incrustations and deposits.

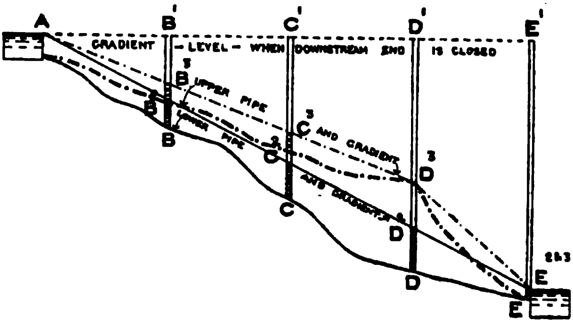
261. Pressures on Pipes.

(a) *Internal Pressure—Hydraulic Gradient.*—The internal pressure is ordinarily due to the head of water which the pipe has to stand; if the downstream end is closed, the head throughout the pipe at any point will be that due to the elevation above it of its upstream end. If, however, the downstream end is open, and the pipe has a free flow through it, the head on it at any point will be reduced from that due to the starting level by the amount consumed by the frictional loss occasioned by the flow. The line joining these pressure ordinates of points along the pipe is called its "hydraulic gradient"; if at these points vertical branch pipes are connected to the main pipe, the water in them will stand at the level of this gradient. When it is necessary to reduce the head, the measures described in Article 259 (*d*) should be taken.

Fig. 145 shows three varying hydraulic gradients. ABCDE is a lower pipe line; when this has a free downstream end the pressure ordinates from it will be BB², CC², etc., and will extend to its hydraulic gradient, which is a straight line from A to E² & ³. AB²C²D³E is an upper pipe line with an elevation at D³ above its general inclination. When the downstream end is free, this divides the hydraulic gradient into two independent sections, AD³ and D³E, and the pressure ordinates, B²B³, C²C³, etc., along the pipe extend to them. It will be noticed that the upper pipe can deliver water at a higher level than can the lower pipe, and that this advantage is secured by the sacrifice of velocity in the pipe from A to D³, which necessitates an increase of its diameter in that length. When the two pipes have their downstream

FIG. 145

PIPE HYDRAULIC GRADIENTS



ends, E, closed, their hydraulic gradients rise to the horizontal line, $AB^1C^1D^1E^1$, level with A, the inlet head, and their pressure ordinates extend to it.

The frictional loss of head occasioned by the flow of water in a pipe is due to the velocity of the flow, the cross-sectional surface and length of the pipe and a coefficient dependent upon the roughness and nature of the pipe. The resistance to flow is due to friction of the water on the inner surface of the pipe, which is a function of its viscosity, and to loss of energy arising from eddies of the water caused by irregularities in that surface; the latter may greatly exceed the former if a smooth pipe becomes deteriorated by corrosion, deposits, etc., or if the interior of the pipe has naturally a rough surface produced by rivets. For low velocities and small diameters the resistance varies nearly as the velocity, and for ordinary and high velocities and large diameters nearly as the square of the velocity, being largely due to internal friction. In both cases the roughness of the pipe much affects the resultant velocity. For long and large pipes the highest velocity permissible is about 3 feet a second; for short lengths this may be considerably increased, and for service pipes of 2 or 3 inches up to 10 feet a second.

There are other losses of head—such as those caused by the entrance of the water into the pipe, sudden enlargements or contractions, bends and valves—but they are usually very small compared with that which takes place in the ordinary length of a long pipe.

(*b*) *Water Hammer.*—When the volume of water in a length of pipe has its velocity suddenly reduced, there is a change in its momentum, which results in an increase of pressure on the pipe. This effect is known as "water hammer"; its amount varies with the decrease of velocity, and the quantity of water affected, which for any pipe varies with its length. It is often increased by rhythmical vibrations due to pumping engines, etc., by the presence of air in the main itself, and by the proximity of a dead end to the closing valve. To reduce water hammer it is therefore necessary that valves which are large in proportion to the diameter of the pipe should be made so that they can be closed only slowly, especially at the end of their travel; the section of the pipe liable to be affected should be short; the transmission of the vibrations of the pumps should be prevented by air chambers allowing water to enter, but not to flow out quickly; the air in the main itself should be given means of escape by air valves, and the number of dead ends reduced as much as possible by connecting them up. Water hammer is usually produced by the quick closure by hand of a valve on the main, but also by the sudden automatic action of large air valves and pressure relief valves (which should therefore be designed so as not to lead to a rapid reduction of velocity), and by hydrants on small branches. There are formulæ for calculating its amount, but as the proper estimation of this is difficult, allowances for it are usually made. In the distribution system where the pipes are small and the effect of the working of hydrants and branches is relatively great, an allowance made is 120 lbs. per square inch for pipes up to 10-inch diameter; for mains from 12 to 20 inches, one from 110 to 90 lbs.; for those from 24 to 36 inches, one from 85 to 75 lbs.; and for still larger ones, one of 70 lbs. per square inch. In the case of large wooden and steel pipes under considerable pressure the additional effect of water hammer will be comparatively small, and therefore an extra allowance for it is not usually made. Where, however, the ordinary pressure is low, one from 25 to 50 lbs. per square inch, varying in accordance with the velocity of the water and the length of the pipe, is desirable.

(*c*) *Thickness of Pipes.*—To the ordinary pressure of the water in the pipe has to be added the allowance for water hammer, and the factor of safety taken is usually 5. In addition an increase of thickness from $\frac{1}{16}$ inch for small to $\frac{1}{8}$ inch for large pipes is permitted to provide compensation for eccentricity in casting. Cast iron should have a tensile strength of from 16,000 to 18,000 lbs. per square inch, and from these data the thicknesses of the pipes are calculated. To ensure a perfect casting the thickness of the pipe should not be less than $\frac{1}{2}$ inch, except for very small pipes, when it should not be less than $\frac{3}{8}$ inch. Manufacturers usually have their own standard of weights of different sizes of pipes, which it is better to accept for small orders; for large ones weights may be specified without adding to the cost per ton. In long mains, when the pressure varies, the calculated thickness of different sections is altered by "steps" of $\frac{1}{8}$ to $\frac{1}{16}$ inch; for small differences the external diameter is kept the same, and the internal one reduced so as to have a uniform size of socket; for large differences taper pipes are introduced at every fourth step, so as to avoid too great a diminution of the bore.

For steel pipes the safe tensile stress may be taken as 15,000 lbs. per square inch on the net area, as compared with a tensile strength of about 60,000 lbs. per square inch for the steel itself. Double riveted pipes have a net area of about 60 to 70 per cent. of the gross area, and the safe stress permissible is thus reduced to about 10,000 lbs. on the gross area. Triple riveted pipes have a net area of about 75 per cent., on which the safe stress on the gross area should be limited to about 11,000 lbs. per square inch. To the pressure of the water the allowance for water hammer has to be added. To prolong the life of steel pipes it is advisable slightly to increase their thickness, say, by $\frac{1}{16}$ inch beyond what theory requires. The formula used is—

$$t=\frac{pr}{s}$$

where t is the thickness of the pipe in inches;

p, the total pressure per square inch on the pipe, including an allowance for water hammer;

r, the radius of the pipe in inches;

s, the permissible stress per square inch on the gross section.

(*d*) *External Pressures on Pipes.*—If a pipe is not properly bedded, the superincumbent weight of the earth or the load placed on it by traffic will tend to bend, and thus stress it. An earth cover of about 3 feet will ordinarily be sufficient to protect cast-iron pipes from injury by traffic, as this will distribute the load. When strengthening is considered necessary, it may be effected by forming a 9 or 12 inch ring of concrete round the pipe. Up to a depth of cover of 15 feet cast-iron pipes do not usually require such support. Steel pipes may be stiffened by angle iron rings, and also by being embedded in concrete. All pipes should have the filling round them consolidated as much as possible by tamping, so as to support them and prevent distortion.

Temperature stresses are generally neglected in the case of cast-iron mains (as the lead joints allow for a certain amount of expansion and contraction), but are allowed for in that of riveted steel ones. It is advisable to provide the latter with expansion joints to eliminate such stresses, and with heavy masonry anchorages at intervals. An earth cover of 3 feet will usually protect a pipe line from heat and from freezing, but in very cold countries as much as 5 to 7 feet may be required. The length of pipe exposed to the sun should be as short as possible; it should preferably have round it a wooden jacket packed with a non-conductor of heat, such as sawdust.

Allowance has to be made for pipes to make them strong enough to resist the considerable stresses due to rough handling during conveyance and laying; this is ascertained by actual experience, and is provided for in formulas and rules for determining their thickness.

(*e*) *Testing Pipes and Mains.*—Before they leave the manufacturer's yard all pipes should be tested up to three or four times the head they will have to sustain when laid. To detect cracks and flaws a pressure equal to a column of water 300 feet high (about 130 lbs. to the square inch) is usually applied. While this pressure is on the pipes are struck with a hammer to find out any weakness or liability to fracture.

As each section of about 1,000 feet of a main is laid, and before it is covered over, it should be tested for water-tightness by hydraulic pressure equal at least to double the head it will have subsequently to withstand, and not less than 100 lbs. to the square inch. The pipes should be kept under this pressure for at least two hours, and while under it should be struck smartly with a 5-lb. hammer. All defects in joints and pipes thus ascertained should be made good before further laying is continued. To prevent during the test excessive expansion owing to the exposure of the pipes to a hot sun, these may be covered over as soon as they have been struck, and only the joints left open, so that any leakage which may occur may be detected. In a properly laid main the amount of leakage should be very small.

After a large main has been completed, it should be inspected from the interior; such inspection has been carried out in a main only 30 inches in diameter.

262. Kinds of Pipes.

(*a*) *General Remarks.*—The usual kinds of pipes are those made of cast iron, riveted steel, or wood; concrete and glazed earthenware pipes have been noticed at the beginning of Article 259 (*d*). Cast iron is most generally used because of its cheapness, durability, and the ease with which it can be made of special shapes. It is practically employed exclusively for the distribution system; it has been made up to 6 feet in diameter.

Riveted steel has now taken the place of wrought iron on account of its greater strength. Being far stronger than cast iron, much lighter pipes can be made of it; it is thus more economically transported, a matter for consideration in new and undeveloped countries having bad communications and being far from the place of manufacture. Transportation is also rendered safer and cheaper by nesting the smaller sizes inside the larger ones. It is especially adapted to long lines with few branches and where high pressures and stresses have to be withstood. The objections to it are its shorter life owing to more rapid corrosion (especially when of small diameter), but this may be overcome in the future by better protective coating. It is difficult to make it into special forms, and its discharging power is only about 85 per cent. of that of cast iron, owing to the roughness of its interior caused by its riveting. Pipes having to resist high pressures (100 lbs. to the square inch and over) and ones of large diameter (4 feet and over) have necessarily to be made of thick metal, and thus can withstand corrosion better than thinner pipes.

Wooden pipes are getting into favour in America; small sizes are bored from solid logs, but large ones are built up in the pipe trench of staves, and are of diameters varying from 1 to 9 feet. Their advantages are economy where wood is cheap and metal dear, they are very durable when kept wet and covered over, they have a smooth surface, which is not affected by corrosion, and they are especially adapted for low pressures for which the minimum thickness practicable for metal pipes would be unnecessarily strong. It is possible that in the tropics proper wood for construction (i.e., that which is straight, long-grained, and fairly flexible) might not be readily obtained, and that the life would be reduced by the great heat and liability to attack by vegetable growth and the destructive white ant.

Cast-iron pipes should have cast on their sockets the initials of the work for which they are supplied, the maker's name, and the year of manufacture; and after they have been tested, their weight should be painted on them. Riveted steel pipes should be similarly marked by paint.

When ordering pipes the following information should be given to the maker:

Kind, pattern, size, and number of pipes and specials required.
Purpose for which wanted.
Maximum working pressure to be borne.
Tabular list of weights specified.
Nature of jointing, painting, and tests prescribed.

An allowance should be made for breakages, which will be especially numerous if the supply has to be sent overseas and to be conveyed across rough country.

(*b*) *Cast-Iron Pipes.*—Pipes above 12 inches diameter are cast in " dry sand " moulds, i.e. in ones which are first dried in a stove. Up to 12 inches they are generally cast in " green sand " moulds, i.e. ones which are not thus dried.

Pipes over 3 inches diameter are ordinarily cast socket downwards, small pipes usually at 45°, and others vertically. An extra length of about 6 inches is cast so as to give additional head and space for the accumulation of impurities, air bubbles, etc., in the metal, and this is subsequently cut off. Whenever a bubble is detected (by sounding with a hammer) the pipe should be rejected as dangerous. The pipe should not have any surface imperfections, which will weaken it and reduce its life, nor any in the interior, which will lessen its discharging capacity by the roughness they cause. A disc ⅛ inch less than the prescribed diameter should pass freely through the pipe. Pig iron re-melted from a foundry should be specified for the metal, and iron direct from the blast furnace should not be allowed. For important works a test bar of standard size (2 inches deep and 1 inch thick) of the metal used should bear without breaking a central load of 30 cwts. when placed between supports 3 feet apart.

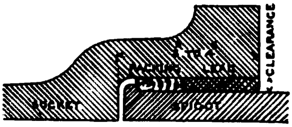
Pipes up to 2½ inches diameter are in 6-feet lengths, larger ones up to 12 inches in 9 feet, and beyond this up to 48 inches in 12 feet lengths ; all lengths are exclusive of sockets. Pipes over 4 inches diameter are not made in fractions of inches in diameter.

A statement giving the weights of different sizes of pipe should be prepared ; generally a margin either way of 4 per cent. for small pipes up to 3½ inches diameter, and diminishing to 2 per cent. up to 36 inches is allowed It is stipulated sometimes that no excess of weight beyond 1 per cent. will be paid for, and sometimes that a margin either way of 1 lb. to the inch diameter will be allowed for each pipe length.

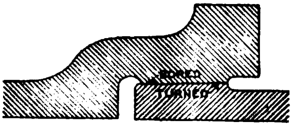
For spigot and socket pipes (Fig. 146) the weight of a socket may be taken as one-fifteenth that of the pipe, and two flanges as equal to 1 foot of pipe. The clearance between the spigot and socket varies from $\frac{5}{16}$ inch for a 4-inch pipe to $\frac{7}{16}$ inch for a 30-inch pipe, and the depth of the socket from 3 inches to 4 inches respectively. The socket should be widened $\frac{1}{8}$ inch at the bottom to prevent the lead being blown out, and the end of the spigot should be formed with a small bead projecting $\frac{1}{4}$ inch to stop caulking material from entering the pipe. There are many forms of socket. In some (Fig. 149, p. 638) a V-shaped or semi-circular groove is formed inside with the object of preventing the drawing of the joint, but the resistance of a plain socket is sufficient to ensure this, and additional resistance may interfere with the expansion and contraction of the pipe line. Moreover, it may not be possible completely to fill the groove with the lead, and a less perfect joint will then result. Socket pipes may be used with greater safety than other forms up to 500 lbs. pressure per square inch, but above that the lead is apt to be forced out of the socket. They are the cheapest form to lay; the flexibility of the lead joint permits expansion and contraction to take place during weather changes of temperature without producing leakage, enables the pipes to be laid to a flat curve or deviation from a straight line, and usually obviates the necessity for expansion joints.

FIG. 146

SPIGOT AND SOCKET JOINT



TURNED AND BORED JOINT



Turned and bored pipes (Fig. 146) have the spigots turned and the sockets bored so as to ensure a perfect fit, and the joints are fixed water-tight by smearing red lead over the ends of the pipes before they are brought together. Such joints are quickly and cheaply laid by unskilled labour, but are expensive to manufacture, and necessitate the laying of the pipes in a rigidly straight line. They are also apt to draw under changes of temperature, and to become leaky if settlement takes place in the pipe trench.

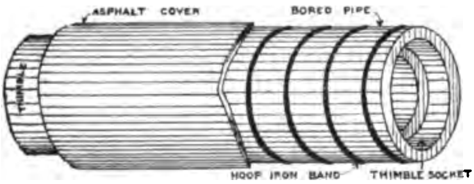
Flanged pipes (see Fig. 152, p. 641) should have their flange faces turned so as to ensure their joints against leakage. If they are not turned, the heads and nuts of all bolts should be made water-tight by placing between them and the flanges "grummets" of rope yarn smeared with red lead or putty. Flanged joints are stronger and easier to disconnect than the other forms, and are always used when the pipe is to be placed vertically or at a high angle.

(*c*) *Riveted Steel Pipes.*—Steel pipes are made of rolled plate of the thickness required by theory after allowing for a factor of safety, and do not need to be formed thicker, as cast iron ones do, to meet difficulties in manufacture, but allowance must be made for the weakening of the section due to the punching of rivet holes. Their weight varies from about one-third to one-seventh that of cast-iron pipes. Small pipes can be made up to a length of 25 feet, exclusive of the sockets, thus reducing the number of end-joints, and as the lead joints can be thinner than the ones required for cast-iron pipes, the amount of lead in the joints is much diminished. Such pipes are usually made with longitudinal lap-joints, either welded or riveted. Large pipes are generally made of single sheets bent and riveted together; the longitudinal joints are double or triple riveted, the circumferential ones are commonly single riveted and well caulked. Butt-joints are preferable to lap-joints, as the latter, especially if the metal is thick and the joints are circumferential ones, obstruct the flow of the water.

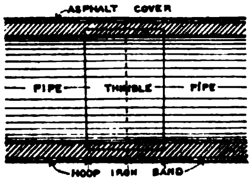
FIG. 147

BORED PIPE

GENERAL VIEW



THIMBLE JOINT



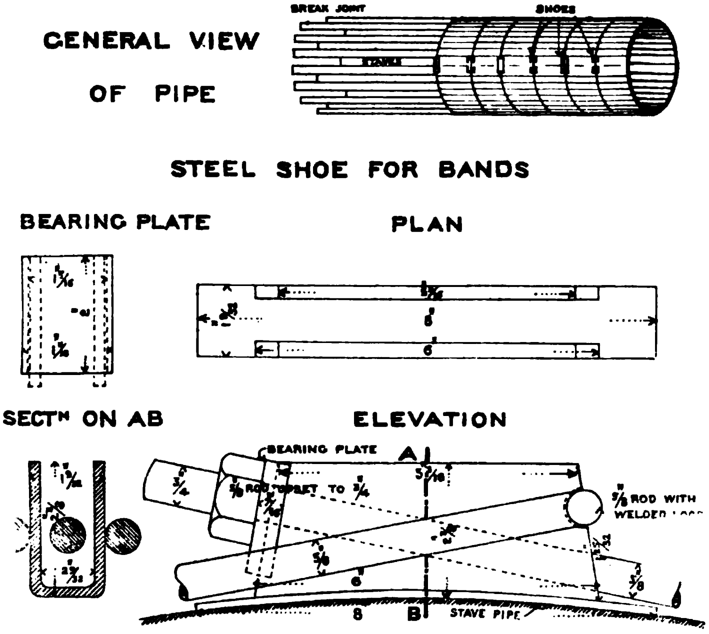
The rivet heads cause eddies in the flow, and the discharge of riveted pipes is thus less than that of smooth pipes of the same bore. The loss by friction in them depends upon the thickness of their plates, which governs the size of the rivets, and the way in which the joints are made.

(*d*) *Wooden Pipes.*—Bored pipes (Fig. 147) are made 8 feet long and from 2 to 17 inches in diameter. The lengths are joined by circular rings or thimbles fitting tightly into mortices in their ends, and they are driven together so as to have a continuous smooth surface. Spiral flat bands of iron are wound tightly from end to end round the pipes with a spacing depending upon the pressure, and the whole exterior is coated with pitch or asphalt.

Stave pipes (Fig. 148) are built up of well-seasoned fir or red wood; the staves vary from 1 inch by 4 inches to $2\frac{1}{2}$ by 8 inches, and break joint in one pattern, but do not in another. The pressure of the water is similarly taken by separate bands of soft steel completely coated with asphalt, and each coupled together by means of a malleable iron or steel shoe, on to

FIG. 148

STAVE PIPE



GENERAL VIEW OF PIPE

STEEL SHOE FOR BANDS

BEARING PLATE

PLAN

SECTN ON AB

ELEVATION

which one end is hooked, while the other, which is screwed, passes through it and is tightened up by a nut until the staves are in water-tight contact with each other. After water is admitted the wooden pipe swells, and is thus slightly indented by the bands, which are oval in cross-section for diameters of 20 inches and under, and circular for larger ones. While by being covered up the wooden pipe is preserved, the metal band is liable to be corroded, as its coating cannot be renewed. It is thus on the durability of the band that the life of the pipe depends.

263. Treatment of Pipes.

(*a*) *Coating.*—This is necessary to protect the pipes, and is applied before they are tested. The "Angus Smith" composition, which is usually specified for cast-iron pipes, now consists of ordinary coal tar or distilled tar thinned with dead oil, and sometimes resin or creosote is added; the mixture is kept at a temperature of about 300° to 400° Fahrenheit. The pipes should be oiled directly they are trimmed in the foundry and before rusting begins; they are then heated to about the same temperature as the tar, and afterwards dipped in it, or, better, the pipe is dipped cold and allowed to attain the temperature of the tar. Sometimes two dippings are specified so as to increase the thickness of the coating. When cool the coating should be hard, tough, smooth, and glossy, should be firmly adherent to the metal, and should be quite free from defects in continuity. Before the pipe is laid any injury to the surface should be made good by asphalt paint or tar varnish.

Riveted steel pipes are not easily coated, but require still more protection than cast-iron ones, owing to the thinness of their metal and its greater liability to corrosion. Ordinarily a similar process is applied to them, but, instead of tar, refined liquid asphalt is used, and is heated to the same extent. Two dippings are often made, and sometimes between them the pipes, while still hot, are wound round with burlap or jute fabric. The joints should receive a further coating just before the pipes are laid. To protect the pipes during conveyance and laying they should be covered with old canvas, etc., and the workmen should wear rubber shoes.

Wooden pipes are coated with pitch, and the bands should be especially well covered thereby, or by asphalt in the case of stave pipes. If the wood is thoroughly seasoned, as is desirable, some consider it should not be coated internally, while others think it should be.

(*b*) *Laying.*—The bed of the trench should be prepared ready to receive the pipes. If the trench is excavated in earth, the bed should be watered and well rammed ; if that is in rock, the excavation should be taken out to 6 inches below grade line, and then made up to it with earth watered and well rammed. The bed should be finished off to the grade line by means of levelled pegs fixed at every 100 feet ; thereafter recesses should be dug to receive the sockets of the pipes. The sides of the trenches should be as nearly vertical as possible, but shoring should not be made except where the soil is bad, or in places, such as roads, where the top width has to be small ; the bottom-width should be at least 12 inches wider than the socket of the pipe, so as to give space for caulking the joints. After the joints have been tested and found water-tight, the trench should be filled by replacing the excavated material in 6-inch layers, watered and well rammed. The depth of the crown of the pipe below ground surface should be from 2 to 3 feet in temperate and warm countries down to 7 feet in those where severe and prolonged frosts may occur.

Before the pipes are laid the inside of them and the sockets and the outside of the spigots should be brushed thoroughly clean, and the pipes should then be lowered in position after all parts of the coating requiring attention have been painted over.

Cast-iron pipes are usually laid from the lowest point or from a valve or special, and generally with the sockets upstream ; some state that the sockets should be at the uphill side when the gradient is long and steep. The spigot should be inserted to its full depth, and for spigot and socket pipes should be carefully centred by means of wedges, so as to make a uniform joint space for the lead, and then kept in position by forcing into the socket jute or yarn, so as to leave open a depth of 1¾ inches for pipes up to 6 inches diameter, and one of 2½ inches for larger pipes, which space should be thoroughly dry. Sometimes a ring of lead is caulked into the bottom of the socket instead of the yarn so as to avoid having decomposable material in contact with the water. The pipes should be packed underneath so as to bear properly throughout their whole length. To allow the lead to be poured into the socket-joint leading rings in two halves can be used for large pipes, but for ordinary-sized ones a simple arrangement is to form a ring round the end of the socket by a single turn of a rope coated with clay, and having its ends opened out and laid across each other to form a pouring inlet. The lead used should be soft and free from tin—best blue pig lead makes the best joints—and should be heated until it is quite fluid. Each joint should be filled at one pouring, and, if necessary, two or more ladles should be used for the larger-sized pipes. After a convenient length has been leaded, the joints thereof should be well caulked by proper caulking tools and hammers of about 4 lbs. in weight, the lead fringes pared off, and the joints left neat and flush with the pipe sockets. In wet trenches two or three lengths of small pipe may be joined together before they are lowered. Large pipes are laid by means of derricks.

Riveted steel pipes should be connected together in as long lengths as practicable before they are lowered in the trench, so as to facilitate riveting. Riveting is usually done by hand, but sometimes by machines, especially when the rivets are large, and after it is finished the joints should be caulked and painted.

Wooden stave pipes are built up in place ; the lower staves are laid in circular cradles, and the upper ones are supported by rings. Care should be taken to bring the staves into water-tight connection with each other, to space the bands correctly, and to protect all thoroughly by the coating. Curves in alignment should be very gentle ones of over 200 feet radius, as to make them even the line has to be bent by means of jacks and braced until a long length has been completed.

(*c*) *Scraping.*—When the diameter of a pipe has been reduced by incrustation, and particularly by iron tubercles, so that its discharge is seriously diminished, it has to be scraped, so as to restore its original diameter and discharge. This can be done by hand or by a special pipe scraper inserted in the pipe line and carried forward in it by the velocity of the water, which is increased by opening a scour valve downstream. When hatch boxes are provided at intervals for the admission of the pipe scraper, the latter is the cheaper process. It is most effective, as it will pass round a curve of radius about fifteen times the diameter of the pipe, and will remove stones, lead, and other abnormal obstructions as well as incrustations.

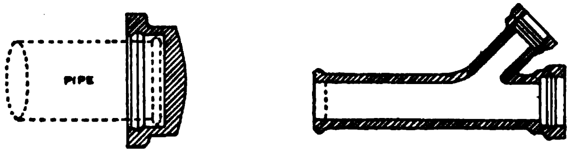
Unfortunately, scraping tends to take off the protective coating of the pipe, and thus to leave that bare and more liable to have iron tubercles formed on it at the expense of its metal. For this reason pipes which may be thus affected and treated should have their thickness increased from $\frac{1}{4}$ to $\frac{3}{8}$ inch to provide for this consumption of the iron. For mains subject to lime incrustation it is advisable to increase their diameters by a $\frac{1}{2}$ inch to permit of a deposit of $\frac{1}{4}$ inch all round. After this is formed it will increase but slowly in thickness, and as it is not much rougher than the original iron surface, it will require scraping only at long intervals.

264. Specials.

Special castings are required to enable the alignment of the main line to be altered from the straight ($\frac{1}{4}$, $\frac{1}{8}$, and $\frac{1}{16}$ bends and offsets); or replacements of broken pipes (sleeves) and stops (caps) to be made; or junctions of branches or different sized pipes to be effected (Y, three-way branches, crossings, and reducing pieces); or appliances to be fixed (T-pieces) to the main. As they are much more expensive than the ordinary lengths, their use should be restricted as much as possible and standard patterns utilised. The angles of specials through which the water has to flow should be as gentle as possible, so as not to reduce its velocity. At sharp curves and angles the pressure tends to force the pipes apart, and this tendency may have to be resisted by anchoring them in masonry, especially where the joints are difficult to make. Specials may have spigot and socket ends, or both ends as sockets. The various forms are illustrated in manufacturers' catalogues, and a few are drawn in Fig. 149. When the cap is used to close a pipe, it forms a dead end; it is also fitted to block a pipe or valve junction not being utilised. The sleeve obviates the removal of several old pipes when a new one has to replace a broken one. It is slipped over the new pipe, which has spigots at both ends, and when this is fixed in position, the sleeve is moved so as to cover the abutting spigots, and leaded so as virtually to form a double socket. The Y branch should take off from near the socket of the main, as this is the strongest position for it. The T-piece can be used for taking off a right-angled branch, or for the junction of a valve. When the valve is a scouring one, the T should be formed leading out from the bottom of the main, so as not to obstruct the flow; for other valves and appliances the T can be turned so as to be vertical or horizontal as required.

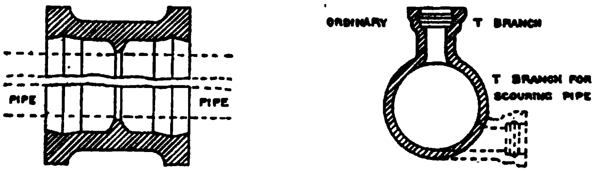
FIG. 149

SPECIALS



CAP

Y BRANCH



SLEEVE

T PIPE

Two-, there-, and four-way branches are formed by specials cast with a similar number of T's.

Riveted steel pipes have changes of alignment made by forming one or more lengths at a small angle. By the use of two or three standard angles of different deflection any curve can be made. Branches for ordinary sizes of pipes are usually of cast iron, riveted or bolted to the steel pipe, and valves are joined to them similarly by means of cast-iron flanges.

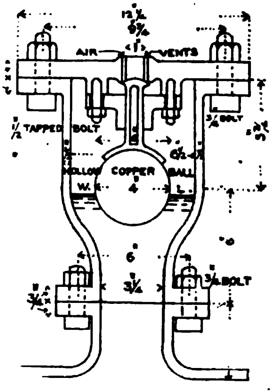
Stave-pipe connections are generally made by inserting cast iron pieces with deep sockets into which the staves are built and well caulked. Reducing pieces are formed by tapered staves.

265. Valves and Appliances.

(*a*) *General Remarks.*—Valves and appliances are illustrated in makers' catalogues, and a selection has to be made of what they stock or can supply. A valve when it is fully open should not in any way block the waterway of the pipe in which it is fixed, as it would thus reduce its discharge; for the same reason the approach to and exit from it should not be formed with sharp bends. The valve should be perfectly water-tight when it is fully closed, but as soon as its opening is commenced may be allowed to work freely on its seat, for which reason it is tapered. It should not stick to its seat, nor bear on it with great friction; to obviate these defects the parts in sliding contact should be faced with brass or gun metal, although for the sake of cheapness the face of the seating may be of planed iron; if both faces were of iron they might rust together. The spindle may be of gun metal or iron, but should invariably work in gun metal bushes or liners. The valves should be protected by covers from damage or unauthorised interference; they should be made of parts easily removable for repairs or maintenance. To reduce the pressure on the back of a large valve when its opening is commenced, a small by-pass controlled by a valve is often fixed, so that by actuating it water can be admitted to the back of the large one. The by-pass may be one-third the size of the main; or, with the same object in view, a subsidiary valve in the main one is geared to and opened before it. Occasionally large valves are made in sections which can be moved independently of each, and thus require less power. Small valves are worked direct by hand, and larger ones by means of gearing, while the largest ones are operated by hydraulic power. Small valves are placed with the spindle vertical, and very large ones with it horizontal, so as to save headway. A valve should be tested for leakage from each side when the gate is closed, and for easy working from the upstream side when it is being operated.

FIG. 150

AIR VALVE

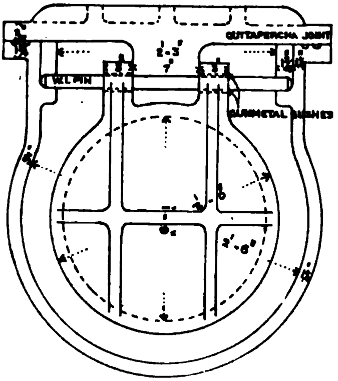


(*b*) *Air Valves.*—As water contains air bubbles, the air is apt to collect at summits of pipe lines, and thus to form obstructions to flow; at such places air valves should be fixed to allow the air to escape. There are several patterns of air valves, of which one is illustrated in Fig. 150. In this a hollow copper ball floats on the surface of the water in the chamber of the air valve, and when this is full, or nearly full, of water the head of the spindle attached to the ball presses water-tight against and closes small air vents pierced through the cover plate. When air accumulates it forces down the water in the chamber, the ball falls with that, thus freeing the holes in the cover, which then allow the air to escape until the water rises sufficiently in the chamber to cause the spindle of the ball to close them again. This seems a better form than that in which the ball presses directly against a rubber disc, and normally closes a hole pierced in this, as the rubber may perish in a hot climate. In another form there is a cup-shaped metal disc at the bottom of the spindle which has an action similar to that of the ball just described. A fourth form resembles the ordinary ball-cock. As the ball suspended from its arm falls when air accumulates in its chamber, the arm also descends, and then uncovers a hole in the casing through which the air escapes. Such valves act also in the reverse way by allowing air from the outside to enter the main when a partial vacuum is formed therein by the breakage of a pipe.

(*c*) *Reflux Valves.*—These valves should be fixed where water would be lost by abnormal reverse flow taking place owing to a breakage of the main normally upstream of them. This might occur in the rising main from the pumping station, or in a rising section of a gravitation main. In both instances reflux valves should be put at the top of the rise, and in the former just below the service reservoir, so that its contents should not run to waste. Fig. 151 illustrates a form of such a valve which consists of a flap in a chamber that is automatically kept open by normal and closed by reverse flow. As sudden closure might produce water hammer (Art. 261 (*b*)), it is best to prevent this by providing a small by-pass outside the valve casing.

FIG. 151

REFLUX VALVE



(*d*) *Safety or Relief Valves.*—The best regulators of pressure are small reservoirs or open stand pipes at intervals along the main (Art. 259 (*d*)), with escapes or overflows limiting the head at them. The water enters such works with a maximum pressure due to the head of the section of the main upstream of them, and leaves the works with one due to their own initial head. Where such arrangements cannot be made, safety or relief valves should be fixed at the downstream ends of long lengths of main, or where water hammer may take place, so as to reduce to the normal any excessive pressure that may occur. Fig. 152 illustrates one form of such valve. In this the valve is kept on to its seat by a spring adjusted to resist the normal pressure; when this is exceeded, the spring

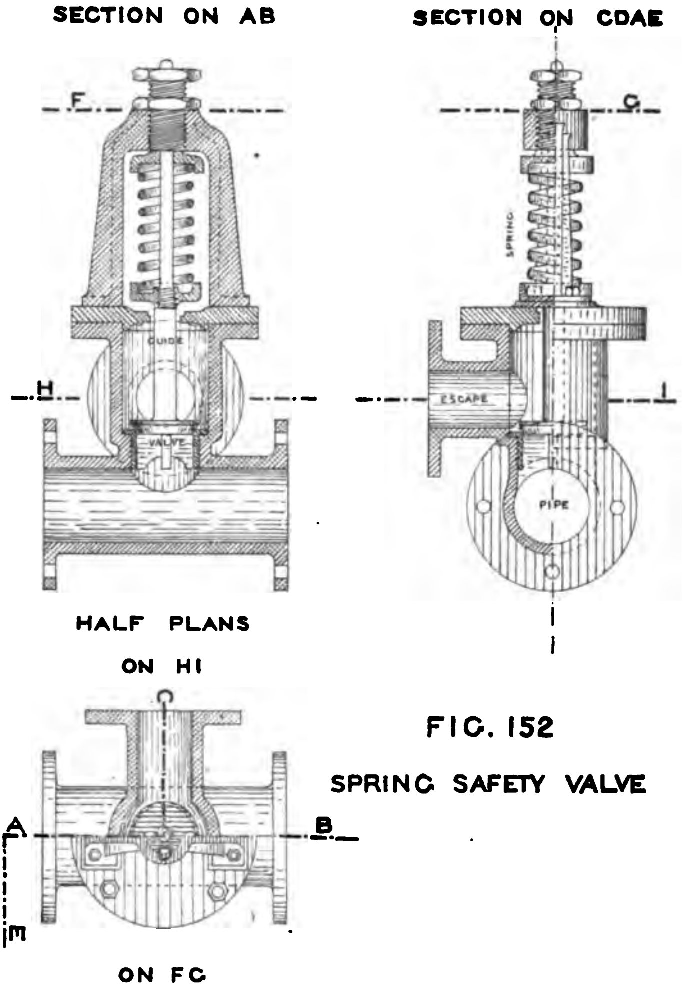


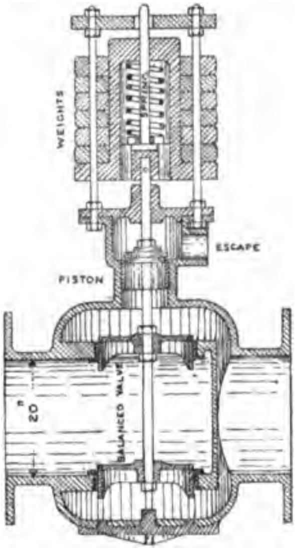
FIG. 152

SPRING SAFETY VALVE

is gradually compressed, and the valve leaves its seat, thus allowing some water to escape by the waste pipe and giving the required relief. A "dead weight" safety valve is objectionable, as its inertia may produce as much water hammer as if the valve did not exist. The advantage of a weight coming certainly into action may, however, be safely obtained by combining one with a spring so that the latter is compressed before the former is raised (Fig. 153). A safety valve must be of large size to be effective, and if the pressure to be resisted is great, the spring must be strong.

FIG. 153

WEIGHTED SAFETY VALVE

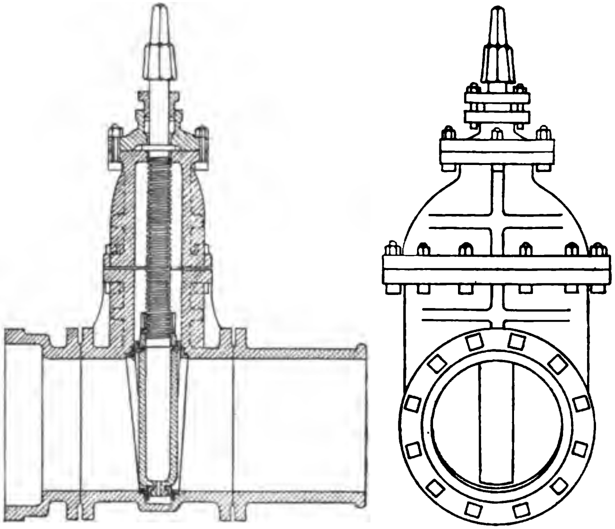


(*e*) *Scour Valves.*—At all depressions scour valves should be provided, so that thereby deposits may be scoured out, or the pipe scraper when in use may be assisted in its action. They are of the simple waterworks sluice pattern, and are worked by hand. They should discharge into a natural drainage, or in towns into the nearest sewer, by the most direct course, so as not to reduce the velocity of flow. As that velocity is likely to be considerable, the area of the scouring pipe and valve need be only one-half or even one-third that of the main.

(*f*) *Sluice or Stop Valves.*—These also are of the simple waterworks pattern. They are introduced into the supply main to divide it into sections, so that if a break occurs in any of these lengths the supply may be cut off by the nearest valve upstream of it. As a valve is expensive, to reduce its cost it can be made smaller than the main in which it is fixed. The consequent loss of head will not be great if the valve is connected on each side to the main by a proper reducing piece. Another advantage of a small valve is that it can be worked by hand by a single man, and this condition might be fixed to determine the limit of size. This form of valve is illustrated in Fig. 154, and is described in Article 280 (*c*) (iv). It is used for inlet, outlet, stop, and scouring sluices.

FIG. 154

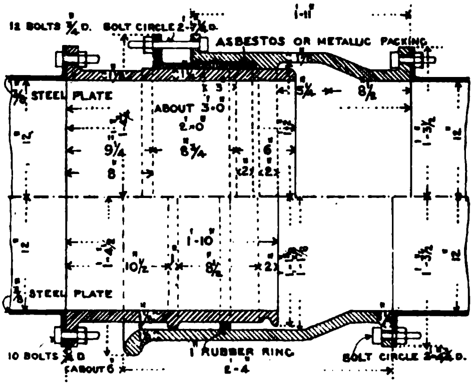
SLUICE VALVE



(*g*) *Expansion Joints.*—These are not usually fixed (Art. 261 (*d*)), but may be required where a length of pipe (such as a long pipe aqueduct over a cross-drainage) is exposed to the direct heat of the sun, especially when that is intense. Fig. 155 illustrates two forms, one similar to a stuffing box, and the other depending upon a rubber ring, which are suitable for small pipes; for large pipes a wholly metallic joint is preferable. In the tropics it does not appear advisable to use perishable material to make the joint water-tight.

FIG. 155

EXPANSION JOINTS



(*h*) *Manholes.*—For large mains these may be inserted at intervals of about 1,000 feet along the line; for large and small mains they should be constructed at the sites of all valves, and it may be desirable to have them at the ends of sharp curves, where distortion may take place. Where cast iron is cheap and in confined situations they may be made of that material of oval form, about 18 to 20 inches long, by 12 or 14 inches wide, and bolted to cast-iron flanges cast with or bolted to the pipe. Where cast iron is dear, the manholes may be built in masonry of larger internal dimensions to give more working space, and these may be reduced near the surface and finished off with cast-iron covers.

CHAPTER XXIII.

PUMPING AND DISTRIBUTION.

266. Pumping Systems.

(*a*) *General Remarks.*—In Article 256 (*a*) it was stated that pumping schemes are to be classed below gravitation ones. They are inferior to the latter, as being more subject to breaks-down, of lesser permanence, and more costly to operate. The cost of pumping is much greater than that of any other item of working expenditure, and therefore its capitalised value should be taken into account when deciding upon the selection of one out of several competing schemes. Pumping is necessitated when water can be delivered to the site of a town only at a level below or but slightly higher than its own, and has to be raised above that site to enable it to be distributed for consumption; if it is possible to get a supply at reasonable cost by gravitation, pumping should generally not be adopted.

Different pumping projects usually have the following parts in common with each other:

The intake works;
The supply main to the pumping station;
Purification works, including sedimentation basins and filter beds;
The pumping station;
The town distribution reticulation.

The systems of pumping are differentiated from each other by the way in which water is supplied to the town for distribution, and are in order of merit:

Pumping to a large high-level service reservoir;
Pumping to a small elevated tank or stand pipe;
Pumping direct to the distribution mains.

(*b*) *Advantages and Disadvantages of Different Systems.*—The advantages of a large high-level service reservoir are that it:

Enables the town distribution to be carried out by gravitation;
Allows the pumps to work at a uniform speed, and for only as many hours as may be desired;
Gives time for petty repairs to the pumping plant to be effected;
May prove economical by the consequent reduction of the diameter and cost of the rising main more than equivalent to its own cost.

Such a reservoir may, however, not be practicable on account of the natural levels, or may unduly increase the total cost of the scheme if the rising main is short.

The advantages of a small elevated tank or stand pipe are that it:

May be the only possible way of gaining elevation for the supply;
Acts by its storage (of, say, an hour's supply) as a regulator for preventing sudden changes in working speed of the engines, which without it would have to adjust themselves at once to fluctuations of the rate of consumption.

The disadvantage is that time is not thereby afforded for petty repairs to the pumping plant.

The advantages of direct pumping are that it:

Gives flexibility by allowing the pressure to be regulated to requirements from time to time;
Visibly shows the variations in the rate of consumption, and may thus be utilised to keep a check on waste;
Diminishes capital cost by eliminating the service reservoir, tank, or stand pipe (Art. 275 (*a*)).

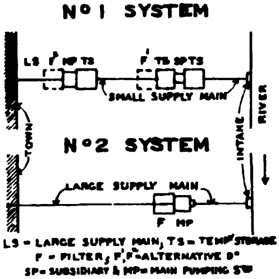
The disadvantages are that it does not afford any storage to regulate fluctuations of supply and to allow of time for repairs. Pumping machinery has, however, now been brought to such perfection that schemes with direct pumping can be made quite reliable, and such are being adopted in cases suitable to them. In them provision has to be made for fire extinction demands in addition to those for ordinary consumption; a minimum allowance of 200 cubic feet per minute has been proposed for this. Such extra provision for pumping need not be made when there is a service reservoir, and possibly not when there is an elevated tank.

267. The Pumping Station.

(*a*) *Location.*—If a temporary storage is arranged for just upstream of the pumping station, this can be replenished by supply flowing to it at the average rate of consumption, i.e. one-twenty-fourth of the daily consumption per hour. The pumping engines have, however, to deliver the total daily supply during the time they are working; thus the pumping rate may be three times the average rate, and the diameter and cost of the rising main from the pumps will therefore be much larger than those of the supply main to them. To cheapen the cost of the combined supply and rising mains the length of the former should be increased, and that of the latter decreased as much as practicable (Fig. 156); in other words, the pumping station should be advanced to the town as far as possible, and this will have the further advantage of facilitating supervision by the superior staff.

FIG. 156

DIAGRAM OF PUMPING

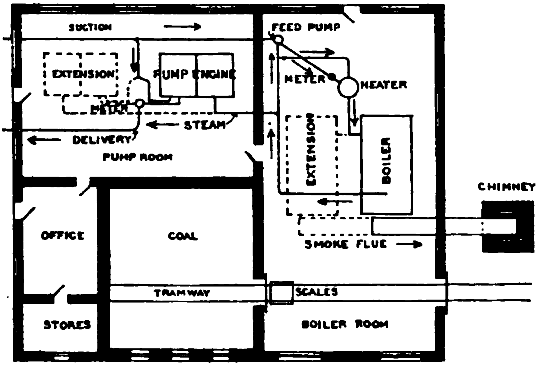

No 1 SYSTEM
LS
F'
MP
TS
F''
TS
SP
TS
SMALL SUPPLY MAIN
TOWN
RIVER
INTAKE
No 2 SYSTEM
LARGE SUPPLY MAIN
F
MP
LS = LARGE SUPPLY MAIN, TS = TEMPY STORAGE
F = FILTER, F',F''=ALTERNATIVE Do
SP= SUBSIDIARY & MP= MAIN PUMPING Stn

If the intake works are at such a low level that the water cannot gravitate from them to where it is desired to place the main pumping station, it may be necessary to have near them a subsidiary pumping station to obtain by lift the head required to enable the supply to gravitate to the main one at the proposed site (No. 1 System); otherwise the main station may have to be located close to the intake works (No. 2 System), or to draw its supply from a low level. If the first mentioned arrangement is adopted, it may be advisable, in order to secure a better site for the purification works, to place them near the subsidiary pumping station and operate them thereby; the effluent from the filters can then flow at the average rate to the main pumping station. This may, however, entail an administrative disadvantage, as it will remove those works further from the town, and thus from superior supervision. If the subsidiary pumping station is some distance off, it should in any case deliver the water raised by it (whether filtered or not) into a temporary storage basin, so that the supply may flow therefrom to a similar basin or suction well near the main pumping station in a pipe of the smallest diameter practicable, i.e. one discharging at the daily average hourly rate. The cost of the temporary storage works has of course to be added to that of the small main in order to determine whether the combination is cheaper than the alternative large main by itself.

(*b*) *Pumping Plant.*—The permanent parts of the pumping station which have a long life—the building, including the chimney for the boilers, and the intake well—should be built of ample size to allow for expansion of the whole waterworks; extra space is also desirable in the tropics to ensure comfort in working. The temporary parts—the machinery of all descriptions—should be of size sufficient only for the requirements of the present and probable developments for, say, the following ten years; further expansion, if necessary, would be met by additional installations. These temporary parts consist of—

FIG. 157

PLAN OF PUMPING STATION



Boilers—including everything for the production of steam, viz. grates, heating surfaces, steam and water spaces, and flues.

Engines—including everything for the utilisation of steam power, viz. steam pipes, cylinders, valves, pistons, air and vacuum chambers, and condensing apparatus.

Pumps—including everything for the raising of supply, viz. water passages, cylinders, pistons, and valves.

The pumping station should be arranged for convenience of work. Fig. 157 is a sketch of an arrangement for a small waterworks.

268. Steam Power.

(*a*) *Definitions.*—Steam power is generally adopted for raising water for town consumption, and will probably continue for many years to be used for this purpose in the tropics. Its energy is measured in "horse power."

One "horse power" is equivalent to the work done in raising 33,000 lbs. of water 1 foot high in one minute, i.e. to 33,000 foot lbs. per minute.

The total horse power required for the pumping engines is

$$\frac{W \times H}{33,000}$$

where W = the total weight of water in pounds raised per minute,

and H = the total height in feet it is raised, including the head lost in overcoming the friction of the rising main.

The "indicated horse power," I.H.P., is the power developed in the cylinders of the engines.

The "brake horse power," B.H.P., is the actual work done in horse power.

B.H.P. $= c \times$ I.H.P. where c is the coefficient of efficiency of the engine and pumps; it should not be less than 0·8, but may be as high as 0·9.

The "nominal horse power," N.H.P., is a term used by some makers to express certain cylinder capacities and dimensions, but is not now generally employed by engineers; it is approximately equal to half the I.H.P., but its amount varies with the maker who uses the term.

(*b*) *Duty of Steam.*—The "duty" of a pumping engine is the weight of water it will raise 1 foot high per unit of fuel used. Originally coal was taken into account, and 100 lbs. of it was used for the unit; however, coal is such a variable material that it is better to substitute for it steam at a fixed temperature (as differences of temperature affect the efficiency of that). A good unit to adopt is 10 lbs. of water evaporated at atmospheric pressure, feed water being admitted to the boiler at 212° F. (which will thus be the constant temperature throughout the evaporation). One pound of the best coal in the best forms of boiler with feed water at 212° F. will evaporate 10 lbs. of water; the expenditure of coal is a measure of the efficiency of the boiler independently of that of the engine. The highest duty is obtained only when the engine is working at uniform speed. Burton[1] gives the following figures:

Engine.	Steam Pressure per sq. in.	Duty, ft. lbs. per 10 lbs. of Water Evaporated.
Large compound engines	90 to 120 lbs.	1,000,000
Small compound engines	—	450,000
Large triple expansion engines.. ..	150 to 160 lbs.	1,200,000
Small triple expansion engines	—	250,000
Large centrifugal pumps (lift not exceeding 25 feet)	—	600,000

In more modern practice the steam pressure of engines driving reciprocating and centrifugal pumps may be said to vary thus:

Large compound engines	90 to 140 lbs. per sq. in.
Large triple expansion engines	120 to 200 lbs. per sq. in.

(*c*) *Consumption of Steam.*—The consumption of steam per I.H.P. per hour in theoretically perfect condensing engines, with boiler pressures varying from 50 to 150 lbs. per square inch, varies from about 9 to 7 lbs., and of coal is about one-ninth of this; in similar non-condensing engines the variation of steam consumption is from about 23 to 14 lbs. and of coal is about one-eleventh of this.

(*d*) *Work Done.*—In ordinary-sized pumping installations 1 I.H.P. pumping into a reservoir against a total head of 100 feet (friction, etc., included) should roughly suffice for 1,000 inhabitants; if the pumping is into the main direct, 1½ I.H.P. will similarly be required. Large engines should be capable of developing one-and-a-half times, and small engines twice the power that will ordinarily be used.

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[1] "The Water Supply of Towns," by W. K. Burton, Assoc.M.Inst.C.E., Crosby Lockwood & Co., 1894, p. 157.

The work done in raising 1,000,000 gallons 1 foot high is equivalent to 10,000,000 foot pounds. If the cost of this raising is accurately taken out, it can be applied to determining the relative costs of different arrangements for pumping and mains.

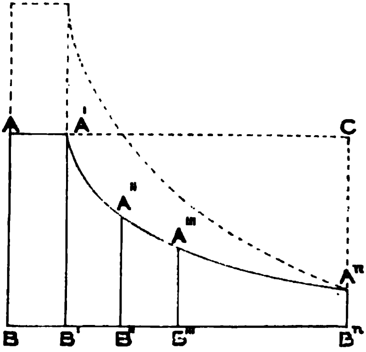
(*e*) *Efficiency of Boiler and Engine.*—Owing to the waste of heat by the products of combustion passing up the chimney, the boiler furnace theoretically makes available only some 83 per cent. of the calorific value of the fuel; the best boilers utilise about 90 per cent. of this percentage, or 75 per cent. of the whole calorific value of the fuel.

As steam supplied to an engine suffers loss from condensation, etc., a perfect engine could utilise only about 25 per cent. of its energy; in actual working the best engines utilise only 17 per cent., and the worst even less than 1 per cent. of the energy of the steam supplied.

(*f*) *Expansion of Steam.*—Steam possesses the property of expansion, and of thus doing additional work without further expenditure of it. This property is made use of in the higher types of high-pressure engines as illustrated in Fig. 158. AB represents the initial pressure on the steam piston, and acts on it for the length AA′, during which the work done is represented by the area ABB′A′; at A′B′ the steam is cut off, and the piston travels to A″B″ under gradually decreasing pressure, as the steam expands, and the work then done is represented by the area A′B′B″A″, and so on, until the end of the cylinder A"B" is reached, when the final pressure is represented by A"B", and the total work done as registered by the complete indicator diagram is AB . . . B"A". If the initial pressure AB had been maintained throughout the stroke, the work done would have been represented by the figure ABB"C. When expansion takes place, the average, or mean, effective pressure is much less than AB, and to enable it to obtain the same horse power its starting pressure must be

FIG. 158

INDICATOR DIAGRAM



correspondingly increased to DB; this explains the utility of high-pressure engines, in default of which larger engines would be necessary to get the same effect. The economy due to expansion is counterbalanced by the increased cost of the engines required to obtain it, and the limit of advantage is thus soon reached.

During the expansion of the steam its temperature falls, and it becomes condensed. If only a single cylinder were used, its size and cost would be great, and the range of its temperature from the beginning to the end of the slow stroke of the pumping engine, and the consequent waste by condensation, would be considerable; by having two (as in a compound) or three (as in a triple expansion engine) cylinders of increasing size this range of temperature is greatly reduced in each cylinder, and condensation in it is correspondingly diminished. In the former class of engine an economical initial pressure is from 90 to 120 lbs., and in the latter one of about 150 lbs. per square inch above atmospheric pressure. A still higher initial pressure might necessitate the installation of a quadruple expansion engine, and would anyhow require a more skilled staff to work it.

(*g*) *Condensation of Steam.*—If the steam after passing through the cylinder is exhausted into the air, the piston will have had to work throughout its travel against a pressure (of about 14·7 lbs. to the square inch) equivalent to that exerted by the atmosphere *plus* frictional resistances (about 2 to 3 lbs.) in the exhaust passages. By passing the exhaust steam into a condenser this back pressure is reduced in proportion to the vacuum therein, and usually 10 lbs. is thus added to the mean effective pressure in the cylinder.

(*h*) *Increasing Efficiency of Steam.*—By Carnot's theorem the greatest amount of work possible from a heat engine is proportionate to $\frac{T-t}{T}$, where, in the case of a steam engine, the temperature measured from absolute zero of the steam at admission (in the cylinder) is T, and at exit (in the condenser) is t. The greater the difference between T and t, the more efficient is the engine; as t is practically fixed, to increase the difference T must be made higher, and this is done chiefly by increased pressure, or, sometimes, partly by superheating the steam (which reduces the waste by cylinder condensation, but has otherwise no thermo-dynamical value).

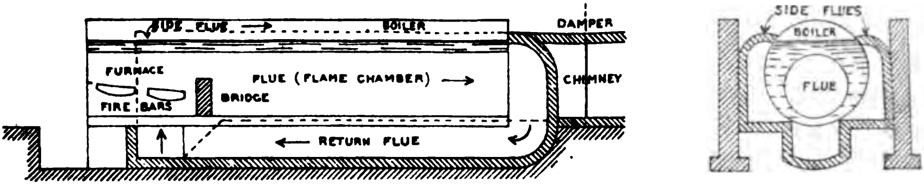
269. Boilers.

(*a*) *General Remarks.*—The boiler is the part of the plant which raises the steam required for pumping, and therefore any type that is suitable for engines of similar power can be utilised in water works. In ordinary conditions a good boiler should be able to evaporate at atmospheric pressure 10 lbs. of water per 1 lb. of the best coal, the temperature of the feed water being 212° F.

Locomotive boilers, and to a smaller degree marine boilers, are designed to evaporate the greatest amount of steam from the smallest amount of water, so as to have the boiler of minimum size. The boiler is traversed longitudinally by fire tubes, through which pass the flames from the fire box, where combustion is accelerated by a forced draught. Owing to the fierce heat and violent ebullition it is difficult to keep the steam pressure constant, and the efficient working of the boiler thus requires highly skilled labour. This type is therefore seldom used for raising steam for pumping engines.

(*b*) "*Shell*" *Boilers.*—The old ordinary forms of waterworks boiler are known as the "Shell" type, and of that the best known varieties are the Cornish, the Lancashire, and the Galloway boilers. The Cornish is illustrated diagrammatically in Fig. 159; the boiler proper, or "shell," is cylindrical, and has flat ends; it is traversed by a single cylindrical flue, about three-fifths the diameter of the boiler, which may be placed centrally, as shown, or to one side, to give more space for cleaning. The heated gases arising from the furnace (which is generally lined with firebrick) pass over the bridge, then along the flue, then downwards to the return flue below the boiler, and thence by the side flues built outside the boiler, and make their exit into the chimney, at the base of which there is a draught-regulating damper suspended by a chain that passes over a pulley, and has a counterpoise at its other end. The bridge is usually of firebrick (but may be of hollow iron in which the boiler water circulates), and rests on the bottom of the flue; it confines the fuel to the furnace and makes the flue in rear act as a "flame chamber," in which the air and the combustible gases are mixed, consumed, and caused to pass on in an eddying stream which facilitates the heating of the water in the boiler; the eddying motion is continued by the devious course of the different flues.

FIG. 159 CORNISH BOILER

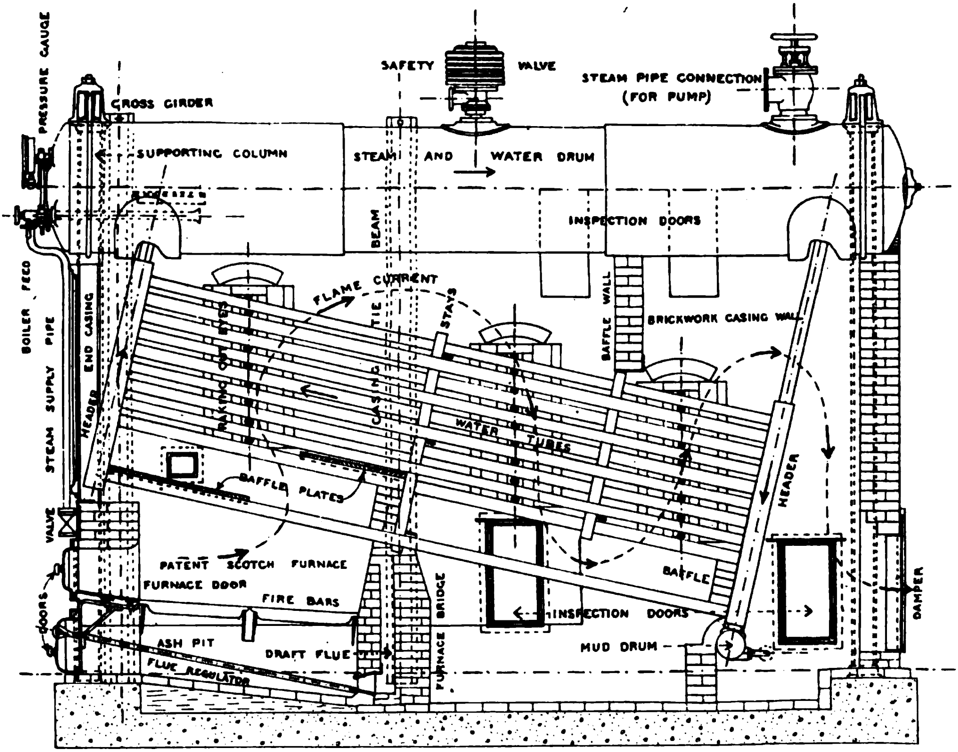


LONGITUDINAL SECTION

CROSS SECTION

FIG. 160

WATER TUBE BOILER



The Lancashire boiler is similar, except that there are two internal, parallel and axial cylindrical flues, each about two-fifths the diameter of the boiler.

The Galloway boiler has.at the furnace end two cylindrical flues, which further on are united into a single elliptical flue with its major axis horizontal, and these flues are connected or traversed by cross water tubes.

The objections to the shell form of boiler are the deficient circulation which involves much time in raising steam, or increasing its amount ; the severe strains to which the shell is subject as it and the water get heated at the top before they do at the bottom ; the greater thickness of metal required by the large diameter which further increases the strains ; and the liability, should an explosion occur, of great damage owing to the large volume of the water. The advantages are the great simplicity in firing and the steady production of an equable evolution of steam.

(*c*) *Water-tube Boilers.*—The tubular, or water-tube, boiler is the most modern form of waterworks boiler. Fig. 160 illustrates one of the Babcock and Wilcox designs. In it the water to be heated circulates in a series of inclined lap-welded wrought-iron tubes fixed parallel to the axis of the furnace, and communicating with each other by their end connections or " headers," and with the thick iron or steel double riveted steam and water drum at top, and the mud drum at the lower end, in which scale and dirt collect until they are blown out from it. The inclined tubes are surrounded by the flames, which thus have a large draught area, ensuring complete combustion and producing a great heating effect. The steam liberated from the tubes is collected in an upper cylinder parallel to them ; although this is of much smaller diameter than an ordinary boiler, it has large steam and water capacity, which results in regularity of action. This cylinder is carried, entirely independent of the brickwork casing, by horizontal girders resting on vertical iron columns ; thus the brickwork can be repaired or removed when necessary without disturbing the boiler.

The advantages of this type are its economy in and rapidity of raising dry steam ; its comparatively easy manipulation and repair ; and the smallness of its individual parts, which facilitates transport to distant countries, and in ones where communications are bad. Unequal expansion is avoided by the rapid and regular circulation of the water, the removal of the thick joints of the tubes, and the top of the cylinder from contact with the flames, and the flexibility of the whole structure; thus the risk of explosion is minimised and the division of the water into small volumes, confined by thin but amply strong tubes, lessens the effect of such rupture. All parts are readily accessible for cleaning; the water tubes get covered only slightly on the exterior by fire dust, etc., as the deposit slips off as it thickens. In fire tubes, as used in locomotives, the deposit is on their interior, and tends to accumulate until it chokes them completely, if they are not cleaned. Lime is, however, likely to be deposited in the water tubes when hard water is used; to prevent such deposit forming in them it is advisable to treat the water in a softening plant before it is admitted to the boiler.

270. Engines.

(*a*) *Classification.*—A steam engine is the part of the pumping plant which utilises the force of steam for working the pumps. Such engines may be classified thus:

(i) Direct or crank shaft with fly wheel;
(ii) Condensing or non-condensing;
(iii) Simple, compound, and triple expansion;
(iv) Horizontal or vertical.

(*b*) *Direct Engines.*—In a direct engine there are two cylinders side by side, each fitted with a three-ported slide valve controlling the steam to it. When steam is admitted to the end of one cylinder, its piston is forced to the other end. When near this end the piston strikes a lever, which actuates the slide valve of the other cylinder, shutting off the steam from the first, and admitting it to the second, and forcing its piston to the other end of that cylinder. When near that end this second piston similarly actuates the other slide valve, thus shutting off steam from the second cylinder and re-admitting it to the first one. The action thus goes on alternately, each piston working the slide valve which admits steam to actuate the other piston. Such simple engines are uneconomical, as they merely force the water ahead, and do not take advantage of the expansive power of steam. They have been improved by the addition of "high-duty gear," which absorbs a certain amount of power at the beginning of the stroke, and gives it back again at the end, thus enabling the steam to work expansively, and to give a duty equal to, or higher than, that of a fly-wheel engine working at the same pressure.

(*c*) *Crank Shaft Engines.*—In a crank shaft engine the motion of the piston is transmitted by its piston rod to a crank which rotates a fly wheel, and the steam is worked expansively. The oldest form of this type is the beam engine originally devised for draining coal mines, but now falling out of use owing to the cost of the foundations required. An ordinary crank shaft engine has the disadvantage that it occupies much space. It should be at least in duplicate, with a duplicate set of pumps, and with the cranks at right angles, so as to get a more uniform delivery of the water. The best form is a "three-throw" engine with three cylinders, and three cranks at angles of 120°, each working a double-acting pump; its delivery of water is nearly uniform, and it is thus well adapted to pump directly into the distribution mains.

(*d*) *Condensing Engines.*—Condensing engines are superior in economy to non-condensing ones, as explained in Article 268 (*f*), that is to say, for engines each of not less than 10 H.P.; condensers effect comparatively little saving with smaller engines, and with these the cost of coal is also a small item of the total working expenses. Condensers are either "jet" or "surface." In the former the condensing water is admitted to the condenser in a jet, and has to be pumped out again by an "air pump," which also removes the air that enters with the water, and would otherwise pass into the cylinder and lessen the vacuum there. This type is much the cheaper of the two, but is best suited to engines working uniformly, and should not be used for ones with varying velocity. In the latter the pumping plant does not require a "circulating pump" to cool the condensing water, as the supply raised by the engine can be utilised for this purpose instead, and it will not be appreciably warmed thereby.

(*e*) *Expansion Engines.*—Simple, compound, and triple expansion engines utilise the property possessed by steam of doing work during its expansion (Art. 268 (*f*)); the first named are sufficient for engines each of 10 H.P. or less, as small plants do not develop much extra duty by compounding. For large engines the higher the pressure the greater the advantage of compounding, and a fairly high initial pressure is necessary to secure the maximum advantage.

(*f*) *Horizontal and Vertical Engines.*—The horizontal engine has its cylinder placed horizontal. Its construction is simple, solid, and economical; it occupies little space, and is easily examined or repaired. As its base is large compared to its height, high speeds may be attained without the vibration caused by other types, and comparatively light foundations are sufficient, and thus money on them is saved.

The vertical engine has its cylinder and moving parts placed vertical. The connecting rod being directly connected with the crank of the driving shaft, that may be either above or below the cylinder. The parts of the engine being arranged compactly, it occupies only a small space, and can readily be examined and repaired. It requires more substantial foundations, and is more subject to vibration than the horizontal type, and the latter is thus generally preferred. Some, however, favour the former, chiefly because it can be adopted where horizontal space is much restricted; it is also useful for deep-seated pumps (Art. 272 (*b*)).

271. Pumps.

(*a*) *Classification.*—The pump is the part of the pumping plant which actually raises the water to be delivered by means of the power applied to actuate it. The principal varieties of ordinary pumps are:

- Displacement Pumps
  - Reciprocating
    - Piston
    - Plunger
  - Rotatory
  - Continuous flow

Impelling Pumps—Centrifugal and jet.
Impulse Pump—Hydraulic ram.
Continuous Lift Pump—Bucket pump.

The forms of pumps are numerous; they are illustrated in the catalogues of their makers and suppliers.

(*b*) *Reciprocating Piston Pump.*—This is the most common kind of pump; in it a piston fitting into a cylinder acts like the piston of a steam engine (Art. 270 (*b*)), alternately drawing in and forcing out the water. If the piston forces the water on only in its forward stroke, it is said to be "single-acting";

if it forces the water on both its forward and return strokes, it is called "double-acting."

(*c*) *Reciprocating Plunger Pump.*—In this the reciprocating part is a solid plunger with a cross-sectional area about one-half of the cylinder in which it works, and this it enters and leaves through packing glands. At the downstroke one-half of the water in the cylinder is forced into the main, and the other half passes to the upper side of the plunger. At the upstroke the water on the upper side of the plunger is forced into the main, and the cylinder is refilled with water below the plunger. This type has the advantage of reducing the number of valves to one-half of those in a double-action piston pump.

(*d*) *Rotary Pump.*—In this type (Fig. 161) two pistons revolving at an angle to each other rotate in a pump case into which they fit accurately, and by their rotation alternately draw the water into the case and force it into the main.

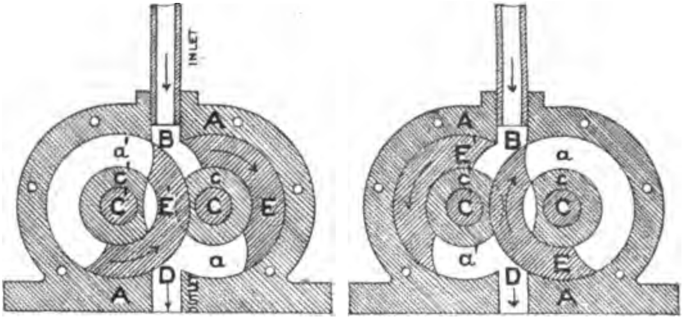


FIG. 161

ROTATORY PUMP

1ST POSITION

2ND POSITION

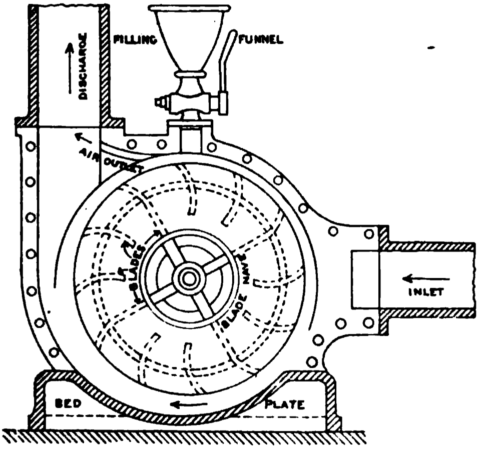
In the figure A is the cast-iron case with its interior formed into two portions of parallel cylinders entering each other; these are in communication with B, the inlet, and D, the outlet. Passing through the case, and the two fixed sockets *c* and *c'*, are two parallel shafts, C, and C', which outside of it gear with a spur wheel of the same diameter, so that they are thereby caused to revolve in opposite directions and with the same velocity. Upon the shafts are fixed two pistons, E and E', each having the form of portion of a ring concentric with the shaft, and the interior surface of the case A. The outer, convex surfaces of E and E′ rub against the faces of the cylinders of A, and their inner, concave surfaces slide upon *c* and *c′*, which are grooved to prevent the water from passing directly from B to D without retarding the pistons. To raise water one of the shafts, C, C′, is set in motion and drives the other, and the pistons E, E′ are rotated in contrary directions. The figure shows that the water entering at B will pass alternately through the annular spaces *a* and *a′*, and will be seized successively by each piston during half a revolution, while the other piston as it revolves will act as a check. Thus the water is ejected through D in a continuous stream, and valves are not required. By reversing the direction of motion of the pistons, that of the water is similarly reversed, D then becoming the inlet and B the outlet.

(*e*) *Continuous Flow Pump.*—The most common type of this is the ordinary chain pump; the endless chain of this works in and out of a pipe, and has fitted on it pistons which fill the pipe. As each piston enters the pipe, the volume between it and the preceding piston is filled with water, which is carried up by the motion of the chain, and is discharged at the outlet as the piston reaches it.

(*f*) *Centrifugal Pump.*—This form of pump (Fig. 162) is really a water fan; it has blades, usually curved, which turn rapidly about a vertical or horizontal axis, and are enclosed in a case. When the blades revolve the water is driven by centrifugal force towards the circumference, and is forced out therefrom into the delivery or discharge pipe; this produces a partial vacuum at the axis, which causes additional water to enter the case from the outer source of supply; the curving of the blades increases

FIG. 162

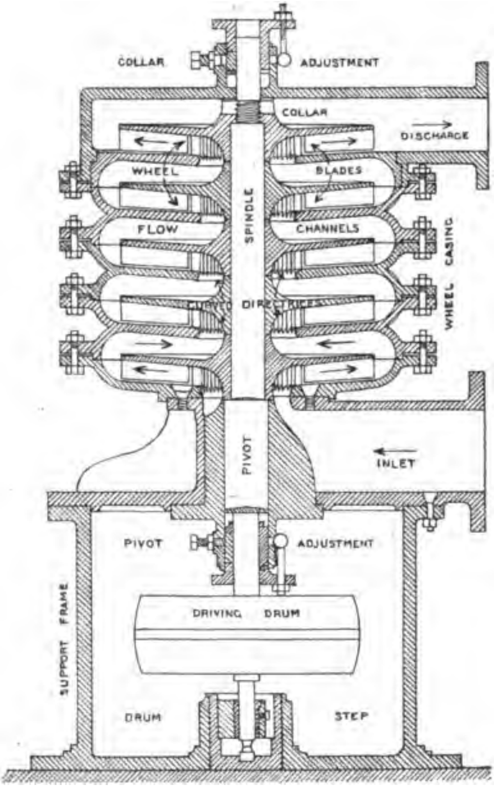
CENTRIFUGAL PUMP



their displacing effect, and allows the water to enter almost without shock, and delivers it nearly tangentially to the outer circumference of the case. The height of suction should anyhow be small, but it is better not to have any suction, and to place the pump below the surface of supply, so that the velocity of rotation may be increased without emptying the pump (Art. 272 (*b*)). The rotatory velocity of the blades is great; a quickening of it will either raise the water to a greater height or increase the discharge. The machine is best suited for raising a large volume to a small height—about 25 feet is a good lift. By placing several centrifugal wheels on the same spindle (Fig. 163) the water from a lower wheel is forced at the pressure acquired by rotation into the next higher wheel near the axis, and passes through that with the additional pressure caused by its own revolution. Hence the increase of pressure due to each wheel is added to that of the wheel just below it, and the final delivery pressure is equal to the sum of the pressures due to all the wheels; the lift of the pump is thus greatly increased without any increase of velocity, but at the expense of the additional power required.

FIG. 163

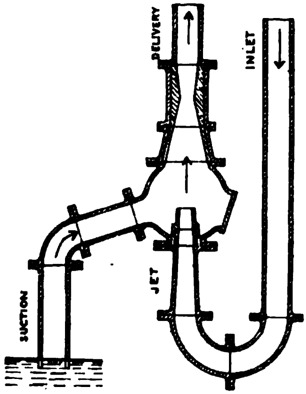
COMPOUND CENTRIFUGAL PUMP



For moderate lifts the centrifugal pump is fairly efficient; it is compact, can pump turbid water as well as clear, is adaptable to a varying discharge of lift depending on its velocity, requires only one valve, the foot valve, and needs but little repair; its chief defect is its great velocity, which cannot be increased beyond the limit which the stuffing of the axis can stand. The hydraulic turbine and Pelton wheel are developments of the centrifugal pump.

FIG. 164

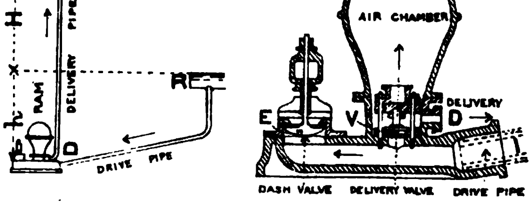
JET PUMP



(g) *Jet Pump.*—Such a pump can be arranged to utilise the velocity of a jet of water, steam, or air, which is delivered through a nozzle, so as to draw with it the water to be raised, and to impart to that the velocity energy required to deliver it (Fig. 164). The vertical height of the inlet pipe should be one-and-a-half times that of the delivery pipe. The pump is not highly efficient, but is useful in connection with a bore-hole, from which it can raise more water than is practicable by any other arrangement.

FIG. 165

HYDRAULIC RAM


GENERAL VIEW SECTION OF RAM

(h) *Hydraulic Ram.*—Fig. 165 illustrates this pump diagrammatically. The water required for actuating the pump falls from the supply inlet R to the ram inlet I, and then through the end of the ram or drive pipe IE. At first it escapes through the escape or "dash" valve E, until its gradually increasing velocity makes that close suddenly on its upper seat, thus producing water hammer (Art. 261 (*b*)); this causes increased pressure which opens the delivery valve V and forces a certain amount of water into the air chamber A. As the pressure in A increases, water is forced up the rising main DS into the supply reservoir S. The delivery valve V closes after the water hammer impulse diminishes, the escape valve E then opens, and the action is thus repeated by strokes. The valve E should be as light as it can be made to resist the jar, and should be as close as practicable to the delivery valve V. The efficiency of the machine diminishes from 0·92 to 0·12 as $\frac{H}{h}$ (the net lift divided by the inlet head), increases from 1 to 25; a large amount of water thus runs to waste compared with the quantity pumped. The ram is simple, compact, automatic, and does not require much attention or repair. It can be arranged so that while inferior water is used for actuating the dash valve, superior, potable water is pumped up the delivery pipe.

(*i*) *Bucket Pump.*—In pumps of this class a series of buckets at equal intervals is attached to a continuous belt or chain conveyor working in a rectangular case or pipe, and dips below the surface of supply, fills, rises, and empties at the crest outlet. Such pumps lift the water only to a moderate height—50 to 60 feet as a maximum—and do not force it to rise beyond the outlets; they are developments of the ancient Persian wheel. As there is free clearance between the buckets and the case, there is a certain amount of slip; this is reduced to about 20 per cent. by the velocity of the chain, which is ordinarily about 200 to 300 feet a minute. The efficiency is good, about 60 per cent. of the I.H.P. of the engine. The pump has the advantage of freedom from liability to be choked.

272. Details of Pumps.

It is important that the delivery of water into the rising main should be as uniform as possible, for power is consumed at each stroke in accelerating the flow from the lowest to the highest velocity, as during the retardation of flow the momentum of the water is destroyed by gravity, and does not give any useful effect to the pump as does the retardation of a fly wheel to an engine.

(*a*) *Stand Pipes and Air Chambers.*—To compensate for irregular delivery an open-topped stand pipe or a shorter closed-top air chamber is installed; these are most effective when nearest to the pump cylinders. In the former the excess delivery raises the column of water in the stand pipe, and the deficient delivery is supplemented thereby; thus work is expended in raising the column, and is subsequently restored to accelerate the water in the rising main; there is, then, however, a loss due to the checking by the piston of the water descending in the stand pipe, and therefore this device is now not often used.

In the latter the action is similar. The excess delivery of water compresses the air confined in the air chamber, and the subsequent expansion of this forces out water to supply the deficient flow in the rising main, but this is done without retarding the piston of the pump. The greater the irregularity of action the larger should be the air vessel to compensate therefor; the size should be at a maximum for high-piston speeds, high lifts, and long rising mains, and at a minimum when the conditions are the reverse. For triplex pumps under low lifts the air chamber may be equal only to a single displacement of the piston, while for single cylinder double-acting pumps it should be from six to eight times that displacement. As air is absorbed by water, arrangements should be made to replenish the air vessel by drawing in a little air with the water as the pump inspires. The vacuum chamber has a similar office of neutralising irregularity of flow, and is fixed to the inlet pipe of the pump.

(*b*) *Suction.*—Suction is the result of creating a more or less perfect vacuum in the suction pipe, etc., whereby water is forced into these parts by external atmospheric pressure. The maximum lift possible by suction is the difference between the height of the column of water balanced by atmospheric pressure, say, 34 feet, and the losses in suction due to influx, producing velocity (and also acceleration when the flow is not uniform), friction in the suction pipe and valve and pump water passage, and to the vapour tension of the water in the pipe. In practice pumps will not draw satisfactorily more than 24 to 26 feet (measured from the surface of the water to be pumped to the inside top of the pump barrel), and it is better to make the suction lift for ordinary horizontal reciprocating plant not more than 18 feet in order to provide for contingencies of working; in fact, any kind of engine will work most smoothly when the water actually gravitates to the pump. To start a pump the intake pipe must either be filled with water, for which purpose it will require a foot valve to retain the water (as in the case of a centrifugal pump which cannot act as an air pump), or the pipe must be exhausted of air by the pump.

Not only should the vertical lift be as small as possible, but also should be the horizontal length of the suction pipe, so as to keep to a minimum the weight of the water contained in it, as that has to be set in motion and stopped at every stroke. For this reason it is desirable to have the pumping well vertically below the pump; a vertical engine is thus advantageous in that its pump can be fixed below the engine-room floor. If a long suction is unavoidable, " three-throw " pumps should be adopted, as with them the velocity of the water in the pipe varies least. As the force of suction will be diminished by air leakage, the clearance given to moving parts must be as small as possible, all fixed parts must be air-tight, and there must not be spaces in them in which air can collect.

When possible, the entire pumping plant should be fixed so as to bring it within easy suction distance of the water to be raised. When, however, the depth from which water is to be drawn is much below the ground surface, the pumps alone should be placed at that distance, and the boiler and engine at the surface with the necessary connection by gearing; a vertical engine is the most suitable for such a condition (end of Art. 270 (*f*)).

(*c*) *Piston and Plunger Speed.*—The piston or plunger speed of a pump must not exceed the capacity of the water to fill its cylinder during each stroke, for if that does not fill it, violent " knocking " will take place, and this will strain the pump and may lead to its breaking down. The speed possible depends upon the size and form of the valves, especially the suction ones, and on the length of stroke. The valves should have large waterways and small lift, should open easily and close tightly and quickly, should have little resistance to flow, and should be simple and readily removable for repair when necessary.

The longer the stroke, especially in crank-shaft engines, the greater the piston speed permissible, as thus the initial acceleration of velocity is reduced. The shorter the suction and the more uniform the discharge of the water, the higher may be the velocity of the piston. The piston speed should easily average 250, and, with well-designed engines, 300 feet a minute without knocking. The slower the speed the more time is there for the cylinder to cool and for condensation to take place; to get the best results a high steam-piston speed is combined by means of gearing with a low pump-piston velocity.

273. Pumping Plant—Miscellaneous Matters.

(*a*) *Various Motive Powers.*—The indicated horse power of the best steam engines is only about 12 per cent. of the calorific value of the fuel, and in ordinary practice is but from 1 to 3 per cent. of that. Internal combustion engines have therefore been adopted in some cases, as these utilise from 16 to 20 per cent. of that value, and in special forms up to 30 per cent.; they have the further advantages that they require little attention, and that they can at once develop power, while getting up steam is a slow process. In such engines a mixture of air and combustible gas is ignited and exploded in the cylinders, and boilers are thus not required.

Electricity has not yet been much used for affording power for pumping plant, but is likely to be adopted in the future when the conditions are favourable.

Hydraulic power has been utilised for motive purposes in certain cases where a large amount of head is available.

(*b*) *The Humphrey Pump.*[1]—This is a novel form in which the expansive action of an exploded mixture of gas and air directly raises the water to be pumped; its action is illustrated diagrammatically in Fig. 166. In its simplest form the pump consists of a bent play pipe, E, connecting the combustion chamber C (in which the gas and air are exploded over the surface of the water) with the delivery tank F, into which the water is forced by the pressure of the expanded gases. After the column of water is set in motion, its inertia continues to carry it forward; the result is that ultimately the pressure of the gases in C falls below that of the atmosphere, and the exhaust valve D opens under its own weight. As the forward motion of the water in E continues, the level in C falls below that in the supply tank G, and fresh water thus enters through the valves H. Finally, when its forward momentum is exhausted, the water begins to flow backwards in E, and rising in C, closes the valve D by impact, and traps above it a cushion A of the spent gases mixed with a large proportion of fresh air drawn in through a scavenger valve (not shown in the diagram) during the forward motion of the water. The cushion of air A is compressed into the head of the chamber by the continued return of the water column, and the latter is thus at last brought to rest, when the pressure of A is much above that due to the static head. In consequence the water column begins a second forward oscillation, causing the pressure of A to become less than that of the atmosphere. By means of interlocking gear the exhaust valve D and the scavenger valve are prevented from opening, while B, the gas inlet valve, is released, and a charge of gas and air thus enters the chamber. When the second forward oscillation is exhausted, a second return flow takes place, compresses the charge of gas and air, and fires it automatically at the proper time, thus starting a fresh cycle of operations.

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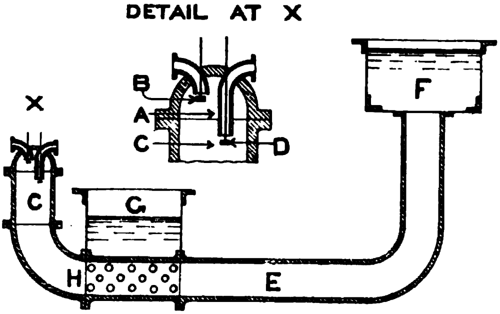
[1] *Engineering*, February 14, 1913; also *The Engineer*, March 14, 21, and 28, 1913.

FIG. 166

HUMPHREY PUMP



This form of pump is particularly adapted to the raising of large volumes of water for low lifts, and is much cheaper in capital cost and of greater efficiency than low lift reciprocating or centrifugal pumps, both of which have low efficiency. At Chingford five Humphrey pumps raise water from 25 to 30 feet for the Metropolitan Water Board from the River Lea to a large artificial reservoir. Four of the pumps are each 7 feet in diameter, and each develops from 200 to 300 horse power, and lifts 40,000,000 gallons a day; the fifth is 5 feet in diameter, and lifts 20,000,000 gallons a day.

When in a sparsely populated area it is necessary thus to obtain a large amount of water at a comparatively small height, it will usually be more economical to construct a storage reservoir at the required elevation, and to lead the supply therefrom by a gravity main rather than have recourse to pumping.

(*c*) *Stand-by Power.*—It is always necessary to have one or more sets of pumping plant in reserve as "stand-by" power, so as to replace a similar number thrown out of use for purposes of cleaning or repair, or which have broken down. In small waterworks, for which one set is sufficient for working, it is usual to have a full duplicate set for stand-by; two sets each of half-power required for working and a stand-by also of half-power would probably cost as much to install, and would furnish less total power. It is thus generally not advisable to subdivide the ordinary working power unless at least two sets each of 10 H.P. are required. In larger waterworks there need be only one stand-by set when the working sets do not exceed five; the largest waterworks with numerous working sets may require two or more stand-by sets.

The stand-by set must be reserved exclusively for its own principal object, and should not be depended upon to meet extra demands for supply such as arise when there is a fire; that object is to meet the contingency of a breakdown, and this is more likely to occur during a time of pressure than in ordinary working.

(*d*) *Working Shifts.*—In large works it is most economical to pump during the whole twenty-four hours in three shifts of eight hours each; in medium-sized works, during sixteen hours in two such shifts; and in small works, during eight to ten hours in a single shift. The reasons for this are that for large works the cost of supervision is proportionately small, while for small ones the excess engine power installed and the supervision are relatively great. The limits of population to be served by the three classes of works in this respect may be taken as 30,000 and over, between 20,000 and 10,000, and under 10,000 respectively.

(*e*) *Selection of Plant.*—The first essential of a pumping plant is that it must be reliable, for a breakdown (in the absence of sufficient stand-by power) would lead to a stoppage of supply, which could not be obviated by temporary expedients. The second is that the character of the plant should be suitable and within the capacity of the local staff to manage efficiently, and to repair in all ordinary minor cases of damage. The third is that the working of the plant should be economical, for which purpose its consumption of fuel should be the smallest possible.

In order that a suitable plant should be installed it is necessary that the waterworks engineer responsible for its selection should have sufficient general knowledge of pumping machinery to enable him to be able to discriminate between the various types offered to him. He cannot be expected to have a detailed knowledge of all the intricate minor parts, especially as these are constantly being modified and improved. He should also be able to conduct, or at least understand, all operations for testing the efficiency of the plant, and to carry out ordinary tests thereof from time to time. Beyond this it is better that he should depend upon the expert knowledge of makers, who are naturally better qualified than he is to design, rather than that he should tie their hands by unsuitable specifications. He should limit his instructions to the general style of the plant and the duty it has to develop, and should further supply information as to the position it has to occupy (including all levels), the conditions under which it will work, and the supply it has to give.

Tenders should be called for from makers of repute, and from them should be selected the one most generally suitable, with such minor modifications as may be desirable. It is advisable to have one tender for the whole plant—boilers, engines, and pumps—so that each part may be properly adapted to its work, and so that the firm entrusted with the supply and erection thereof may be solely responsible for everything connected therewith. For this reason that firm should design the chimney and the setting for the boilers, and should be bound to work and maintain the plant for a specified period after it has been started.

274. Service Reservoirs.

(*a*) *General Remarks.*—Service reservoirs are the temporary storages of the water to be delivered for consumption, and form the heads of town distribution systems. In gravitation systems they are at the tail of the supply main, and in pumping systems at that of the rising main. In all complete schemes they are filled with filtered water; it is only in less perfect ones that they are supplied with unfiltered water. The amount of their storage capacity depends upon the nature of the purpose for which they are installed (para. (*c*)).

The principal objects of a service reservoir are:

To regulate the supply as required by the demands of consumption; they are filled at an average rate, and are drawn upon at a fluctuating rate (end of Art. 276 (*b*)). They thus enable a reduction to be made in the size of the supply main, and to a certain extent avoid the necessity for its duplication and the provision of stand-by pumping plant.

To allow the pumping engines to work under fairly settled conditions of non-fluctuating discharge under approximately constant head.

To permit filtration to proceed at a regular and steady rate.

To let the distribution system be supplied at a fairly constant head.

To provide for meeting abnormal demands, such as arise on the outbreak of a fire.

To lessen the cost of the distribution reticulation by shortening the principal mains, which are the most expensive ones.

To render the distribution reticulation more elastic in working when there is more than one service reservoir.

To reduce the total pumping lift when there is more than one service reservoir.

To give time for the repair of the rising main and (if there is no stand-by) of the pumping plant.

(*b*) *Location.*—The location of a service reservoir is principally determined by the natural levels of the ground, for any artificial raising of the work very greatly increases the cost. A small district of the town lying at a slightly higher level than the other parts can, however, be served cheaply by forming in the main reservoir a subsidiary high chamber (with the same full-supply level) which can be kept filled and thus give a constantly high supply. In this case the cost of pumping the whole of the water to full-supply level should be avoided by admitting by valve regulation into the chamber only the quantity required to replenish it from time to time.

The bed level of the main reservoir should be high enough to command the town for fire-extinguishing purposes, unless pumping is depended upon for these (Art. 279 (*c*)).

The physical nature of the ground is also a determining factor, as sound water-tight foundations are necessary for the reservoir. The level at which the bed of the reservoir should be placed is influenced by both these conditions; the work may be wholly in excavation, partly in excavation, or all above ground; the second of these locations is generally the cheapest and best if otherwise suitable. Town sites are naturally expensive, and may also be restricted in area and costly in the matter of foundations, if in the course of time the surface level has been raised owing to deposit of material in building operations, etc., or if old excavations exist. Another objection to a town site is that it may lead to contamination of the supply; for this reason some prefer to place the reservoir a little distance from the inhabited area.

(*c*) *Number of Reservoirs.*—If only a single reservoir is to be built, it should be located as centrally as possible in the town, so as to give the most uniform and highest pressures, and require the smallest size of mains. If two reservoirs are proposed, one should be on the side of the town where the rising main enters, so as to reduce the length and cost of that, and the other on the opposite side of the town. If the levels of the town vary considerably, three or more service reservoirs may be desirable, one on the side nearest the pumping station, and the others centrally with respect to the districts they serve. These districts should be formed, not with reference to town wards, but to the topographical levels; thus with three works they would be respectively the high-level, middle-level, and low-level reservoirs and districts. The Montmartre Reservoir, Paris, is a single structure, having three floors, thus concentrating supervision in one place and effecting economy in foundations, and in having one instead of three roofs. Such a construction is best suited to a central hillock commanding the whole town, and having its districts at different levels conveniently close to it. If, however, the districts are distant from each other, there would probably not be any total economy from such a design, as the mains to the lower districts would be increased in length and cost.

The rising main would serve each reservoir direct, for if a lower one obtained its supply from an upper one, that would involve the expense of pumping the combined supply to the higher level. If, however, it is desired to economise in the cost of the rising main, the length branching off to the lower reservoir could be made of correspondingly smaller diameter, but at the extra expense of pumping against the increase of head due to the consequent greater friction. Several reservoirs effect economy in the pipe system; each would serve independently its own district, except that the districts would be connected with each other to meet abnormal conditions.

(*d*) *Capacity.*—In old schemes as much as two or three days' supply was contained in the service reservoirs with the object in view of providing time for repairs of parts of the systems upstream of them. The expense resulting from this large provision was great, but another objection to it, subsequently ascertained, is that the long storage of filtered water has a tendency to make it deteriorate bacteriologically (Art. 249 (*h*) (iv) and (v)). The main purpose to be served by a reservoir is that it should meet the fluctuating demands of consumption. It has been calculated that a storage of from 1·5 to 3 hours' average consumption is sufficient to ensure this. To meet the requirements of a day of maximum consumption these figures should be increased by 50 per cent., i.e. to from 2·2 to 4·5 hours' average annual hourly consumption. Another principal purpose of a reservoir is to supply water for the extinction of a fire; the quantity required for this compared to that normally drawn off for consumption decreases with the number of the population, and in America has been estimated at a day's consumption for a town of 5,000 people, and at 6 hours' for one of 100,000, at an average consumption of 100 gallons a head per day. Thus this purpose is of greater importance in the case of a small town, and of less consequence in that of a large one. These figures seem very liberal, especially for an extra provision, as in a great emergency ordinary supply could be temporarily shut off, and direct pumping through a by-pass would be an additional assistance. A third principal purpose of a reservoir is that its size should suffice to provide supply when the works upstream of it have to be shut off for emergent repairs; thus the longer the supply main the greater should be the storage capacity of the reservoir. In the case of gravitation systems necessitating possibly long repairs such storage should be given by simple tail reservoirs of large capacity (Art. 259 (*e*)); in that of pumping schemes a provision of half-a-day's supply should be ample. The last named appears to be the controlling consideration, and thus the storage capacity of a service reservoir should generally be equal to half-a-day's average daily supply.

Not only must the reservoir provide time for the repair of works upstream of it, but it must also allow time for its own cleaning. This is done by constructing it in two or more compartments, so that one can be thrown out of use when necessary, and supply given by the others. As cleaning is seldom required, and can be postponed until the daily consumption is small, it is rarely necessary to have more than two compartments, and thus the cost of and area occupied by additional partition walls are saved. If extensive repairs are necessary, which should rarely be the case, supply should be drawn from each compartment alternately with, if required, aid from direct pumping through the by-pass until they are completed. Direct pumping could be resorted to in such an event were there only one compartment, but it is not advisable to economise to such an extent, as thus there would then be no storage capacity to rely upon for contingencies such as an outbreak of fire.

(*d*) *Shape.*—The form of a reservoir depends greatly upon the dimensions of the area on which it has to be built. A circular plan has the advantage that with it the bounding wall can be reduced, not only in length, but also in section, as the masonry will resist earth pressure by compression as a ring, and does not require the dimensions necessary for it to withstand such pressure by its weight alone. Such a plan has, however, the disadvantages that it is wasteful of the ground area, is difficult to roof, and cannot readily be utilised in extensions of the reservoir.

The square is the most economical rectangular form in regard to its bounding line, but its partition wall will have a greater length than if that were constructed parallel to the shorter side of an oblong plan. Long compartments have, however, the advantage of separating the outlet and inlet further apart, and thus keeping the contents more quiescent or from passing direct from one to the other, when both are in operation together.

(*e*) *Depth.*—The depth of the reservoir usually varies from 12 to 16 feet, and, occasionally, is 20 feet, or in rare cases still greater; generally, 12 feet is sufficient, although some prescribe 15 feet as the minimum; the greater depths are often necessitated by the limitations of the area available. In addition, there should be a further depth of 18 inches along the central valley line of the bed to allow for sediment to deposit. A shallow reservoir decreases pumping charges and pressures on mains, but increases the temperature of the water and the liability of vegetation to grow in it.

(*f*) *Forms of Reservoir.*—Reservoirs may either be formed with earthen side slopes or be constructed in masonry. The former is unsuitable for the temporary storage of filtered water unless the bed and sides are faced with concrete, which will be expensive; it is better to treat such a work as a tail reservoir, and make it large enough to hold several days' supply (Art. 259 (*e*)); it will therefore usually not be possible to locate it in the town itself. A masonry reservoir should contain only about half-a-day's supply, and with this small capacity can generally be built inside the town. Reservoirs have been designed with circulating partitions projecting from each side alternately, and extending nearly to the opposite side, so that the water as it fills the compartment has to traverse the narrow sinuous course thus formed, and stagnation is prevented. For works of small storage this refinement seems unnecessary, but if desired can be adopted by making the supports of the roofing, not as separate piers, but as continuous walls pierced for circulation at alternate ends. In plan certain reservoirs have been made with arched ends to the bays into which the compartments are divided by the piers carrying the roofing, so as to strengthen the side walls. This is an expensive and apparently not a necessary arrangement.

(*g*) *Constructional Details.*—It is essential that the reservoir should be impervious to percolation through its bed and sides, particularly if it is located in a town. Open earthen reservoirs have therefore had their beds and sides lined with asphalt, but this material is softened, and may flow gradually under the heat of the sun, and its behaviour under water has not yet been sufficiently tested. It would seem better to depend upon good puddle walls and trenches in the centres of the banks, and good trench drains outside them if the levels permit percolation water thus to be intercepted and passed off.

Masonry walls and floors have been backed with or laid on puddle, in order to make them retentive. Sounder practice would appear to be to depend rather on cement pointing and plastering of the water faces, and on filling settlement cracks with cement grouting; also to surrounding the outside of the work with good trench drains, and dry backing of the walls in connection with these. An expensive design has the bed formed with a double bottom, the upper one being supported by barrel vaults carried on the lower one, and through these all pipes are led.

Side walls are usually built with their water faces vertical, or at most with a batter not exceeding 2 inches to the foot; they must be made amply strong to resist the earth and water pressures to which they are subjected. Their foundations and those of the roofing piers must be well spread out to prevent unequal settlement and the consequent formation of cracks. Angle junctions of the masonry walls and floor should be rounded off to facilitate cleansing. Walls may be of rubble masonry, concrete or sound brickwork; reinforced concrete would have the effect of preventing temperature and settlement cracks. The reservoir floor may be of concrete at least 18 inches thick, and each compartment should slope down to a central valley gutter for the collection and disposal of sediment. If the stored water contains free carbonic acid gas it will tend to dissolve hydraulic lime mortar, and that should not be exposed to attack; the side walls should then be built with hard insoluble stone or brick cement pointed, and the floor should be cement plastered, so that an increase of the hardness of the water may be prevented.

(*h*) *Roofing.*—The objects to be secured by roofing are:

To keep cool the water stored in the reservoir;
To keep cool the masonry of the reservoir, and thus avoid temperature cracks;
To prevent dust, etc., from entering the reservoir;
To stop mosquitoes from breeding in the reservoir;
To obviate the growth of vegetation in the water.

To gain these it is highly desirable to roof all reservoirs, and especially those on town sites.

SERVICE RESERVOIR ROOFS

FIG. 167 MASONRY ROOF

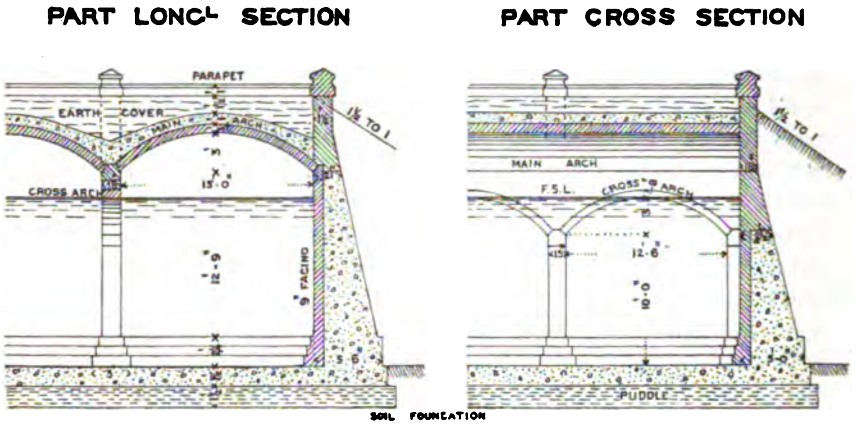
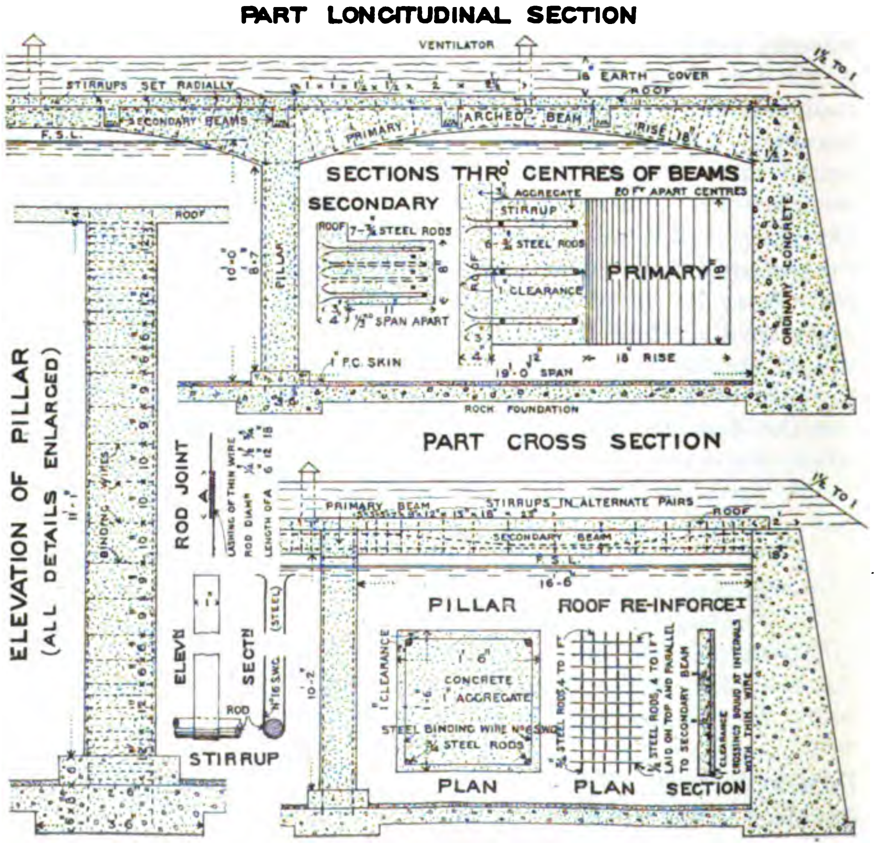


FIG. 168 RE-INFORCED CONCRETE ROOF



Roofing may consist of—

Brick or masonry jack arches carried on piers or partition walls;
Reinforced concrete slabs supported by reinforced beams similarly carried;
Tiling or corrugated sheeting on ordinary trusses.

The third form is cheaper than, but inferior to, the other two in attaining almost all the objects desired. Figs. 167 and 168 illustrate the first two forms. The earth cover should not be less than 18 inches in temperate, nor than 2 feet thick in tropical countries, and should be drained by under drains leading out of the earthwork enclosing the reservoir. The roof should have ventilators, and these in the tropics should have gauze screens to prevent the entry of mosquitoes; also there should be a manhole entrance to each compartment.

(*i*) *Control Arrangements* (Fig. 169).—These may consist of the following:

(i) *By-pass or Direct Main.*—To allow supply to pass direct to the town, and not through the reservoir if this has to be thrown out of action.
(ii) *Reflux Valve.*—To prevent stored water from returning down the rising main when that is broken; the valve should be fixed in the supply pipe just before that enters the reservoir.
(iii) *Expansion Joint.*—To provide for the effect of expansion of the rising main.
(iv) *Automatic Inlet Valve.*—To shut off water automatically when the reservoir is full. The valve is closed by the rise of a float in a separate small chamber at the inlet to the reservoir.
(v) *Inlet Pipes and Valves.*—To admit water to each compartment of the reservoir.
(vi) *Outlet Floating Pipes and Valves.*—To pass supply to the town from each compartment; the inlet end of each pipe is maintained by a float at about 2 feet below the water surface of the reservoir, so as to get the purest supply.
(vii) *Overflow Pipe.*—To discharge excess water accidentally admitted into the reservoir. In the partition wall between the two compartments should be an

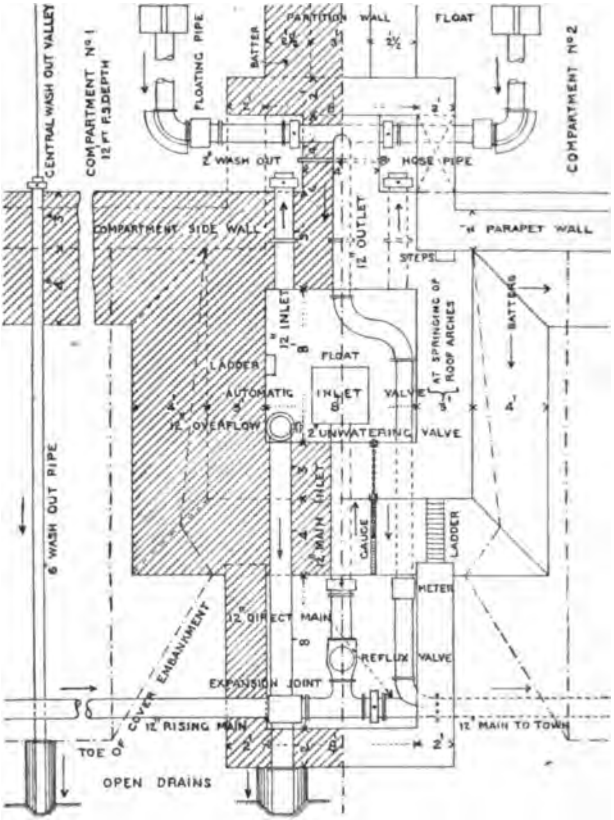
overflow notch, with its sill at a level so that such excess may pass into a compartment when empty rather than run to waste from the other.

(viii) *Wash-out Pipes and Valves.*—Each set to run off at

FIG. 169.

SERVICE RESERVOIR CONTROL ARRANGEMENTS

FOUNDATION PLAN FINISHED PLAN



intervals the water charged with sediment at the bottom of each compartment of the reservoir when it is desired to clean the compartment. Each pipe should have its inlet at the centre of the end wall of the compartment ; it will probably be brought into use when some 3 feet of water is in that compartment, and the pipe should be able to run the water off, say, in three hours. Frequently the wash-out is combined with the overflow so as to have one rear drain in common to both.

(ix) *Hose Pipe and Valve.*—To utilise the storage in one compartment for washing the walls and floor of the other. The pipe is a short one laid through the partition wall near its base, and a hose can be attached to either end of it for washing out.

(x) *Gauge.*—To register the depth of water in each compartment ; this should be arranged so as to be readable from the outside of the reservoir.

(xi) *Meter.*—To measure the rate at which consumption takes place.

Fig. 169 illustrates how these arrangements may be disposed in a compact way.

275. Water Towers and Stand Pipes.

(*a*) *General Remarks.*—When there is not a site available for a service reservoir, either on account of deficient area or elevation, a water tower or a stand pipe may be substituted for it. In order to diminish the cost of these the highest site possible should be selected for the work, and one as close as practicable to the pumping station, so as to reduce the length of the rising main connecting the two. Pumps have recently been so much improved that the tendency is to depend upon them alone, and to omit water towers and stand pipes, which are expensive structures, particularly the first named ; they also increase pumping charges, as with them all the supply has to be raised to the maximum height.

(*b*) *Water Towers.*—A water tower may be defined as a small elevated service reservoir of the minimum size—usually equal to one hour's average consumption—which will equalise the working of the pumps, so that they need not follow the momentary variation of the consumption, but may be given time for adjustment to meet the average fluctuation of the draw-off during the period for which the storage of the water tower suffices. It is chiefly of use for a small town for fire extinction purposes, and may for it be given a somewhat greater relative capacity than is sufficient for a large town. In both cases a fire will probably start in a single house, and for some considerable time will extend to about the same area, and thus the water storage to cope with it should not vary much. The tower might be utilised as a fire look-out observatory.

The water is stored in a cylindrical metal tank preferably made of steel plate riveted like a boiler. The height of the tank should be equal to its diameter, which is an economical proportion and will present a better appearance than a taller one, although tastes differ in this respect. The whole of the water contents being at the elevation required can be drawn upon; the tower is thus superior to a stand pipe as in that the use of the water in the lower part of the column is only to support the contents of the upper part. The bottom of the tank was originally made flat, and was supported by beams; it is now made either conical, segmental, or hemispherical. The last named is the best, as it produces the lowest stresses, since the tension in it at any point will be half that in the base of a flat-bottomed cylinder of the same radius; it, however, requires more complex details at the supports at the circumference of the vertical cylinder from which it is suspended.

Additional support can be given to the bottom by a central column, which may be utilised as a stand pipe when the tank so thrown out of use, or for a staircase giving access to the tank. The main support of the tank may consist of a steel trestle having four, six, or eight legs (the last two are more expensive than the first, but present a better appearance), and these must be securely anchored to resist lifting action by wind when the tank is empty. A more architectural treatment is to build the support as a masonry tower. Great care is necessary to have perfectly secure foundations, as any settlement of them will much change the stresses in the tank.

As a water tower is a top-heavy structure, it is best not to construct one in a country liable to earthquakes. Where one is there necessary a trestle support should be preferred; it should be of wrought iron or steel, and should not have any combination with cast-iron parts; a masonry support is less secure against shocks.

The tower should be provided with control arrangements similar to those described in Article 274 (*i*).

(*c*) *Stand Pipes.*—A stand pipe is a column of water designed so as to produce a fairly constant head against which the pumps will work, and which will afford steady and sufficient pressure in the distribution system. Only the upper part of the water in the column is effective; the lower part serves but as a support to that, and the part of the pipe containing it having to withstand the greatest water pressure, is expensive to construct. Unless the stand pipe is made of large diameter (when it virtually becomes a costly and elongated water tower) it will have only a small equalising effect on the fluctuations of consumption draw-off, and these will therefore have to be met by varying the speed of the pumps correspondingly, and almost immediately as they occur. The stand pipe is thus much inferior to the water tower; all the aid it gives to the system is to act as a cushion to the engines and as a shock absorber to the distribution pipes. The modern practice is to substitute for it wrought iron air vessels near the pumps of size sufficient to meet these requirements.

Formerly in England stand pipes were designed as breeches pipes with a central upper length above the bifurcation bend, and with connecting cross-pipes between the two legs. This was necessitated by the then type of pumping engines which worked efficiently only against a constant head. The single column stand pipe is now constructed there, as it also is in America, and is formed of soft open-hearth steel plate riveted like a boiler.

A stand pipe is subject to water pressure, wind pressure, and in cold countries to the action of ice. The effect of water pressure is less than that of violent winds, which may cause the stand pipe to slide on its base or to overturn. Good and solid foundations are therefore necessary, and the stand pipe should be securely anchored to them. To prevent the formation of ice, which has caused many accidents in Amcrica, it is necessary to encase the pipe in wooden sheeting, or preferably to enclose it in a masonry shell; this on account of its slimness has not a good architectural appearance, but that may be gained by building it as a wider tower with a staircase in its interior. Such a tower will also obviate the effect of wind pressure, but will add considerably to the cost of the stand pipe.

276. Distribution Calculations.

(*a*) *Preliminary Arrangements.*—For calculating the sizes of the different mains of a distribution system, the first thing to be done is to prepare a map of the town showing its streets and contour levels, and on this to arrange, after trial and inspection on the ground, the proposed system of reticulation. For this purpose the town should be divided into districts, and if the levels vary considerably, these districts should be arranged into zones (Art. 274 (*b*)), in each of which the elevation will be within certain pre-determined limits. Next, the rate of consumption of each district should be estimated from the number of its population and the various services—municipal and commercial—which have to be supplied. The provision for consumption should take into account not only the existing demands, but the probable increase thereof in the near future—say, ten to twenty years according as the growth may be rapid or slow. As fire extinction is so important a consideration, the local Fire Brigade should be consulted as to the additional provision to be made for the supply for that purpose of the different districts in accordance with the importance of their fire risks. It will make calculations simpler if all supply demands are reduced to a common basis, that of population at the rate proposed to be allowed for consumption per head. After the lines of the principal mains have been laid down on the map, those of the branch mains should be fixed; subsequent to the construction of the reticulation the map should be kept up to date in respect not only to the pipe lines, but also to the various appliances—hydrants, valves, etc.—connected therewith.

The cost of the distribution system is usually the most expensive part of a waterworks project, and therefore the arrangements for it require careful study in order to secure a properly sufficient service to every part of the town at the smallest charge practicable. That cost will depend partly on the length of the mains and partly on their sizes, which have to be regulated by the demands of consumption. To facilitate estimation it will be advisable to determine accurately the rate per foot run of each of the diameters of pipe selected; this may be done by taking into consideration a certain number of lengths of pipe (say, for the smaller sizes 11 number, equal to 99 running feet), and calculating the detailed cost thereof in respect to all items of materials and labour.

(*b*) *Discharging Power of Pipes.*—The sizes of the pipes have to be calculated with reference to their discharging power, the velocity in them and the pressure head they will afford; various tables are published of the first two, and these will be of great assistance in making selections between alternative arrangements. A simple formula for discharge of the ordinary length of a long pipe is[1] —

$$G=\sqrt{\frac{(3d)^5+h}{l}}$$

where G is the discharge in gallons per minute,
d, the diameter of the pipe in inches,
h, the head of water in feet, and
l, the length of the pipe in yards.

From this the following rules can be deduced:

(i) When the length and diameter are constant, the discharge varies directly as $\sqrt{h}$;
(ii) When the head and length are constant, the discharge varies directly as $\sqrt{d^5}$;
(iii) When the discharge and diameter are constant, the head varies directly as the length;
(iv) When the length and discharge are constant, the head varies inversely as $\sqrt{d^5}$;
(v) When the head and diameter are constant, the discharge varies inversely as $\sqrt{l}$.

The particulars for any one size of pipe can thus be applied to ascertaining quickly the similar information for another size of pipe.

The discharge which has to be taken into account is that of the maximum rate of consumption, and in addition the allowance for fire extinction. The former has been variously estimated by different authorities to be equivalent to the passing of the whole day's supply in from six to ten hours, but the time is usually taken as eight hours, i.e. the maximum rate to be provided for is three times the average rate throughout the whole day.

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[1] "Practical Hydraulics," by Thomas Box, E. F. N. Spon, third edition, 1873, p. 94.

(*c*) *Velocity—Size of Pipes.*—To enable the mains to be self-scouring the velocity in them should vary from 2½ to 3 feet per second; another rule gives the variation in rate from 2½ feet for a 4-inch pipe to 7 feet per second for a 36-inch pipe; a rule for rising mains is that the velocity in them should vary from 200 to 400 feet a minute. These rules take into account the great increase in loss of head due to high velocities, and do not apply when the head naturally available is considerable. The fundamental formula for determining velocity is that due to Chézy, and is—

$$v=c\sqrt{rs}$$

where v is the mean velocity of the water in feet per second;

r, the hydraulic mean depth $=\dfrac{\text{area}}{\text{wetted perimeter}}$; this in cylindrical pipes is equal to one-fourth of the diameter;

s, the virtual slope, or hydraulic gradient, of the water in the pipe which is equal to its head divided by its length;

c, the coefficient of friction or resistance to flow.

Various authorities have devised from this other formulæ in order to get the correct value of c, but their results differ greatly, e.g. when v is 3 feet per second and for pipes from 3 to 48 inches diameter by 20 per cent., and in certain cases by a still higher percentage. As the condition of the surface of the pipe so greatly alters the velocity of flow in it (see also Art. 261 (*a*)), it is impossible to devise a formula which will give correct results in all cases. Moreover, the usual description of pipe is not sufficiently exact to enable its discharge to be predicted within 10 per cent.

Flamant, after carefully investigating many experiments, has proposed the following formulæ which give a small margin of excess:

For new cast-iron pipes .. .. $v=86{\cdot}38d^{\frac{5}{7}}s^{\frac{4}{7}}$
For pipes slightly incrusted .. $v=76{\cdot}28d^{\frac{5}{7}}s^{\frac{4}{7}}$

where v and s represent the factors noted in Chézy's formula above, and d is the diameter in inches.

D'Arcy's formula gives fairly average results; it is—

$$v=\sqrt{\frac{2grs}{\zeta}}$$

where g is the acceleration of gravity$=32\cdot2$ feet per second, and

$\zeta=0\cdot005\,(1+\frac{1}{12}d)$ for new and smooth pipes.
$\zeta=0\cdot010\,(1+\frac{1}{12}d)$ for incrusted pipes.

The formula gives less than two-thirds the velocity (and thus less than two-thirds the discharge) of new pipes for incrusted pipes.

As pipes continue to deteriorate it is better to allow a small margin of excess unless the provision for the number of the population to be served has already been made liberally. Pipes liable to the formation of tubercles or to much incrustation (Art. 260 (*a*)) will require a larger margin than those which are likely to remain unaffected and clean. A common rule is to calculate the size of clean pipe required theoretically, to this to add 1 inch, and then to allow for the next larger commercial size. Sometimes for pipes exceeding 12 inches in diameter the sizes ordered differ by 3 inches, and for ones exceeding 36 inches by 6 inches when the lengths of the mains concerned are not great, as makers quote a cheaper rate per ton for large supplies of one diameter than for smaller quantities of different diameters aggregating the same length; a further economy results from the consequent reduction in the number of special and spare pipes necessary. In this connection not only has the purchase price of the pipes to be taken into account, but also the increased expense of transporting and laying unnecessarily large diameters; usually it is best to keep to the sizes calculated.

(*d*) *Pressure Head.*—The pressure head at any point of a pipe or main is equal to that at its commencement, less the loss due to the frictional resistance to flow up to that point. It is as well to tabulate calculation results, district by district, of effective head above ground level at different points, and this can be done in a statement form somewhat as follows:

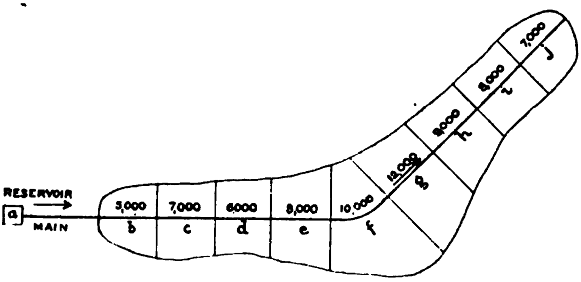
1. Section of pipe or main (as lettered on the distribution plan for reference).
2. Reduced level of ground at head of section.
3. Population, etc., served by pipe.
4. Average number of gallons per minute discharged throughout pipe at maximum rate of consumption.

5. Size of pipe (allowing for incrustation) in inches (required to serve the population below the head of each section).
6. Length of pipe in yards.
7. Head at commencement of section in feet.
8. Rise (+) or fall (—) of ground level in feet.
9. Total statical head at end of section in feet (7) ∓ (8).
10. Loss of head due to friction in section of pipe in feet.
11. Effective head at end of section in feet (9)—(10).
12. Reduced level of ground at end of section (2) ± (8).

The effective head at any point (11) must suffice during the time when consumption is at its maximum to give supply at a fair rate to the top storey of the highest building in the area served, and also for fire extinction purposes. If the calculated head available is excessive, the diameter of the pipe can be reduced, thus correspondingly increasing the frictional loss; if it is in defect, the diameter should be increased to diminish such loss. Fig. 170 is a diagram showing how for such a tabulation a main is divided into sections, which are lettered for reference and have indicated on them the numbers of the population to be served finally thereby. The required reduction in the diameter of main is made at the head of the section concerned, and that diameter is adhered to until the next reduction is necessary, i.e. the pipe has its size reduced at intervals, and is not tapered uniformly throughout its length.

FIG. 170

DIAGRAM OF MAIN SERVICE



277. Systems of Supply.

There are two main systems of supply—the intermittent and constant services. In the intermittent service each house had a cistern of capacity sufficient for a day's consumption, and this was filled from the mains daily in about a single hour, after which the supply was shut off. As each consumer had to utilise supply carefully, or to run short of it, this led to economy; also pressures on the house pipes were reduced and waste from leaky fittings thus lessened. There are, however, two great objections to this kind of service. First, the cistern being generally located in an inaccessible position near the roof, or below a top floor, was seldom inspected or cleaned, and the supply in it became contaminated by dust, dead mice, etc., etc., and, anyhow, deteriorated by long storage. Second, the mains being shut off for most of the day, were not immediately capable of furnishing water for fire extinction. These objections have led to the discontinuance of this form of service.

In the constant service water is admitted to the house pipes throughout the twenty-four hours from the town main direct, and is thus in constant circulation and is supplied fresh. The objections raised to the introduction of this system were that it would lead to great waste by defective fittings unable to keep water-tight under the high pressure, and to extravagant use by consumers; these objections at first proved well founded. They have been met by improved fittings, and by municipal measures of inspection and control (Art. 248 (*f*)); this system is now adopted in all modern waterworks.

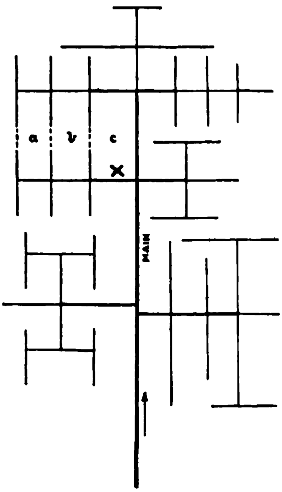
There is a third system sometimes installed which might be called the intermediate service. This combines the constant service with cisterns, and thus introduces the defects of the two other systems. It is best that water to be consumed should not pass through a house cistern; the only cisterns which should be allowed are those for water-closets and for the hot-water service. The former (including the main cistern) should have removable closed tops, should be controlled by ball cocks, and have ample overflows; both kinds should be readily accessible, should be provided with cuts-off for use in case of accidents, and should be quite separate from the ordinary house supply. If, however, a cistern for consumption water is fixed, it should be placed so as to be easily inspected and frequently cleaned, and should have a removable tight-fitting top and a ball cock; its effect will be to reduce the pressure in the house service from that of the town service to that due to its own elevation; it is only when the former is high that the introduction of such a cistern is justifiable. It is also of use in furnishing a certain amount of water close at hand at the outbreak of a fire.

278. Systems of Distribution.

(*a*) *General Remarks.*—In a complete system of distribution every street built upon should have a pipe laid in it, and the reticulation should keep pace with the extension of the town; when designing the system it will suffice to provide only for the probable growth which will take place in the next fifteen years. The pipes should be aligned throughout at a fixed distance from the centre lines of the roads, and should be graded approximately with them; hydrants to act as air valves should be fixed at crests and others as scour valves communicating with the sewers at depressions. Branch pipes should as a rule be controlled at their heads by valves, and the valves should be arranged symmetrically, usually near the kerb line. Hydrants are generally placed on the same side of the street as the supply pipe, and are connected to the largest pipe available.

FIG. 171

DEAD END SYSTEM



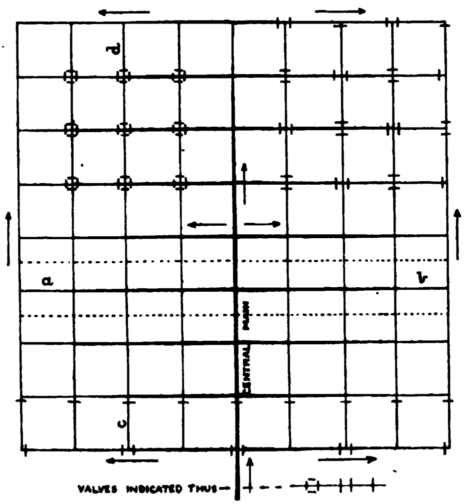
There are three systems of distribution—the "dead end," the "gridiron," and the "ring"; the two last are best adapted to towns regularly planned with streets at right angles to each other.

(*b*) *Dead End System.*—This is illustrated in Fig. 171, and consists of a main with independent branches from it, all terminating in closed or "dead ends." It is best suited to the supply of streets planned irregularly in a small town, or in a district of a large one having considerable length compared with its breadth; for the latter it can be combined with the gridiron system. Its advantages are that it is easy to calculate the diameters of the independent pipes in it, and that any part of the system can be shut off by closing a single valve such as at X. The disadvantages are that water stagnates and deteriorates in quality at the dead ends, and deposits are liable to collect there; unless there are many valves a considerable area has to be shut off when repairs are necessary; and there is not any intercommunication between the pipes. The first can be met by flushing the dead ends, but at the expense of waste of water; the other two may cause inconvenience in general supply and danger in the case of a fire.

(*c*) *Gridiron System.*—If the ends of the branches at *a, b,* and *c* of Fig. 171 are connected with each other, a commencement is made of the "interlacing" or "gridiron" system. The complete system is drawn in Fig. 172, which shows that full intercommunication is thereby ensured, thus letting every pipe be supplied from all directions, a great advantage when a fire has to be extinguished. Stagnation of water anywhere is prevented, and the size of the areas shut off while repairs are being effected may be made small. These are the advantages of the system; the disadvantages are that the circulation prevents the exact calculation of the sizes of the pipes; that numerous valves are required; and that it is difficult to apply district meters (Arts. 248 (*f*) and 281 (*b*)). In regard to the first it may be assumed that each branch, *ab*, taking off from the main has to supply half the districts bordering it on each side, while the branches, *cd*, at right angles to them and parallel to the main afford only subsidiary supply, and thus provide a factor of safety during periods of abnormal draw-off.

FIG. 172

GRIDIRON SYSTEM



In Fig. 172 at the top left-hand corner a complete system of valves is shown, i.e. with four valves at each pipe intersection, so that only two valves have to be closed to shut off a length of pipe, and that length is reduced to the minimum. At the top right-hand corner the number of the valves is reduced by half, but to shut off any pipe four valves (and thus three other pipes) have to be closed. At the bottom is an arrangement by which only three valves have to be closed to shut off a pipe, and thereby not more than two others.

In regard to district meters the number can be reduced by shutting off one district from another by valves and admitting all water to serve each district at one inlet leading to its meter. If the meter is installed to ascertain the consumption rate during the day, the district intercommunication valves would be closed throughout the twenty-four hours; if it is intended to detect thereby only wastage by leakage during the night, those valves need only then be closed and inter-district circulation can be permitted during the day time. Of course, the valves would be opened on the occasion of a fire, but the delay in obtaining full supply due to the time necessary to do this is naturally an objection to the described isolation of the district; during that time, however, the district would have its own individual supply.

There are two ways in which the internal reticulation can be designed—first, by assuming that each distribution branch, *ab*, serves half of the district on each side of it, and is fed by the outer mains at each end of it, while the minor pipe lines, *cd*, simply serve the streets through which they run and unite the district together; second, by treating all the internal pipes as supply lines and making them in each direction of similar diameter. The first arrangement would best suit a large, and the second a small district.

(*d*) *Ring System.*—This is illustrated in Fig. 173; the ring mains branch off on two sides from the supply main, and return to meet each other at the opposite side so as to enclose the district, each branch of the ring being made capable of serving half the district.

In this Figure the gridiron and ring systems are contrasted. The diameters in inches of the pipes and mains are those given by Mr. Rudolph Herring[1] from which he calculates that in these examples the weight of pipes in the ring system exceeds that in the gridiron system by 14·5 per cent.; this is due to the more circuitous course of the water in the former. He states that a pipe system should be designed to deliver at all points a given quantity of water per minute at a given pressure, and that this can be accomplished at the least cost by bearing in mind that—

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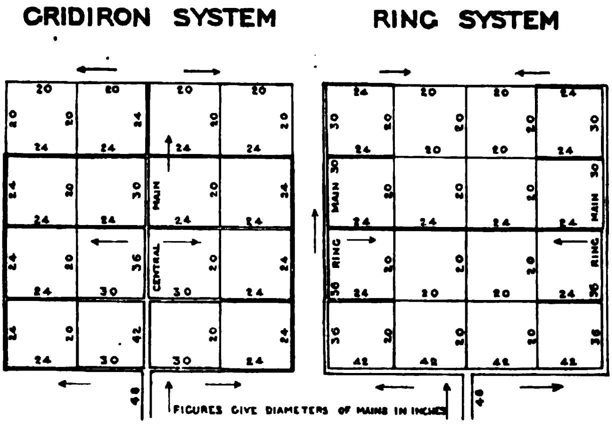
[1] "The Economic Design of Water Distribution Systems," by Rudolph Herring, *vide Engineering News*, Vol. LXII, No. 7, p. 172, dated August 12, 1909.

FIG. 173



FIGURES GIVE DIAMETERS OF MAINS IN INCHES

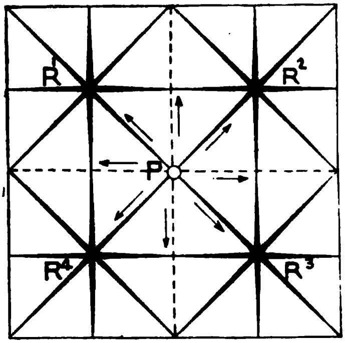
(i) A pipe carrying a certain quantity of water will cost less than double of a pipe carrying half that supply, therefore a maximum concentration is economical;
(ii) The shorter the distance to which the bulk of the water is carried, the shorter will be the larger pipes, and therefore the less costly will be the distribution;
(iii) The more direct the bulk of the water is delivered to a given point, the less is the friction head and the greater the remaining available pressure for the same size of pipe, which produces further economy.

(*e*) *Centres of Distribution.*—It has hitherto been assumed that the supply enters the town from one side only, in the direction of its greatest length; a considerable economy will, however, result if it can be arranged to enter at the centre of that length, and to have the principal mains bifurcating in opposite directions therefrom and axially along the divisions of the town thus made.

At the end of Article 274 (*c*) it was stated that several service reservoirs serving their own districts independently would effect economy in the pipe system; they thus become centres of distribution as shown diagrammatically in Fig. 174, at R¹, R², R³, and R⁴. If, however, the pumping plant has to pump directly into the mains, small water towers or stand pipes, it will, if practicable, be best to have the pumping station in the centre of the town, as at P, and to supply the centres of distribution by rising mains located along the interior diagonal lines drawn, PR¹, PR², etc. This shows the advantage in town-planning schemes of having main diagonal streets, and the advisability of drawing up such schemes so as to take into consideration the requirements of water supply, and also of sewerage, which will equally benefit thereby. Similarly, the more the streets are laid out to conform to contour levels the easier will it be to design these town services.

FIG. 174

CENTRES OF DISTRIBUTION



The question whether it would be more economical to have four centres of distribution, R¹, R², R³, and R⁴, as shown in the diagram, or a single central one from P, would have to be determined by alternative estimates. Assuming that from the principal mains from P (along the principal diagonals and dotted cross-lines marked by flow arrows) there would have to be branch mains following the similar lines of the four-centre system to give similar command, the reticulation of the latter would be somewhat larger than that from the former, as for it supply pipes would have to be laid in addition to and parallel to its rising mains, PR¹, PR², etc. The diameters, and thus the costs, of the rising mains of the four-centre systems between P and their own centres would, however, be less than the similar supply lengths of the one centre system, as the former would be made large enough to discharge only the average rate pumped during the day, and would not, like the latter, have to meet the much larger maximum rate of consumption which has to be provided for comparatively short periods. This saving on the four-centre rising mains would meet the extra cost of their parallel supply mains either wholly or partly.

279. Fire Extinction Service.

(*a*) *General Remarks.*—In England waterworks were at first designed chiefly with reference to the ordinary requirements of consumption ; in America from an early date greater importance was attached to the necessity for making sufficient provision for the extraordinary additional demands for fire extinction. This latter view is now generally held in England also, and throughout a waterworks system there mains are designed to give at the same time supply sufficient for consumption and fire extinction ; this implies that the diameter of the larger mains has to be determined with respect to both demands, and that of the smaller ones chiefly with regard to the latter. Generally in India not much attention has as yet been given to protection from fire. In Article 274 (*d*) it has been stated that the provision for fire extinction is relatively greater than that for consumption in small than in large towns. It is true that a large town may have a more extensive and more prolonged fire than a small one, but the capacity of its water service is naturally better adapted to deal with such a conflagration. As a district increases in population, the provision for fire extinction will increase much less than that for consumption.

(*b*) *Amount of Supply.*—The full quantity of water required to extinguish one or two large fires occurring at the same time must be provided ; in gravitation schemes, especially those from storage reservoirs, it will generally be easy to increase the rate of supply ; in pumping schemes it is often specified that the pumps must be capable, regardless of efficiency, of delivering 20 per cent. more than the normal supply in cases of emergency ; in such conditions, when absolutely necessary, the reserve of pumping power of the stand-by engines may be called upon, although it is not advisable thus to depend upon them in ordinary circumstances (Art. 273 (*c*)). Similarly, it is not desirable to pump unfiltered water into the mains which normally distribute filtered water, but the risk attendant on this of introducing pathogenic germs into the distribution system may then have to be run. Ample storage in service reservoirs is of the greatest use (Art. 274 (*d*)) ; the diversion of the normal supply for consumption to fire extinction is a practical measure to take, and as it is not likely to last long, will not cause much inconvenience to consumers, who, anyhow, will recognise its necessity. In regard to the amount of storage for fire extinction, Mr. Burton[1] suggests the formula $Q=200\sqrt{P}$

where Q is the minimum storage in cubic feet ; and
P is the population.

(*c*) *Pressure.*—The pressure in the mains necessary for fire extinction depends upon how that is to be effected—either direct from the hydrants or by means of fire engines ; in small towns the former system is the best, if practicable. In large towns the latter is generally adopted, and for economy in working the pressure in the mains is ordinarily limited to what is sufficient for normal consumption, say, from 20 to 35 lbs. per square inch according to the class of building concerned ; when a fire occurs the storage reservoir has then to be cut off and the extinction supply has to be furnished by the pumps working at high pressure. The lower the pressure the more numerous should be the fire hydrants. For gravitation schemes where a high pressure would entail extra expense, 60 lbs. for residential districts and 70 lbs. for business ones may therefore be allowed ; for pumping schemes the pressure may vary from 80 to 100 lbs. These are the pressures for direct fire extinction, and at the actual hydrants during times of maximum consumption. The pressure of the pumping station itself may vary from 100 to 160 lbs., but as pressures of over 130 lbs. may lead to breakages, this limit should not be exceeded over large areas of the reticulation. Where the ground levels vary greatly, the reticulation should be laid out in zones (Art. 274 (*b*)), so as to ensure sufficient, but not excessive pressure. In ordinary Indian towns much smaller pressures are allowed, partly because the houses usually are low, and partly because fire service is less thoroughly provided for.

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[1] " The Water Supply of Towns," Crosby Lockwood and Son, 1894, p. 206.

(*d*) *Fire Streams.*—In America the discharge allowed for a fire stream is from 175 to 200 gallons for a residential district, and about 250 gallons a minute for a business one. There the average number of fire streams which may be required simultaneously is thus estimated according to the population of the towns:

Population ..	1,000	5,000	10,000	25,000	50,000	100,000	250,000
Fire streams ..	2–3	6	9	12	18	24	48 (36?)

These seem high, especially for the largest population (for which the figure in brackets would conform better to the general scale), but no doubt are necessitated by local conditions. Mr. Burton (on p. 191) considers that the principal mains of a fairly large European city should be capable of discharging at least 200 cubic feet per minute in addition to the absolute maximum consumption, and states that this additional quantity will require mains of from 12 to 15 inches diameter with ordinary town hydraulic gradients. This discharge is equivalent to about 1,250 gallons, and thus to some six fire streams of 200 gallons a minute; if the population is taken as 50,000, this allowance will be one-third of that given above for an American city of the same size, and is an indication of how local conditions affect the amount of the supply. He says (p. 207) that the extra pumping power required to raise 200 cubic feet per minute against a head of 100 feet is nearly 40 H.P. As every pipe in the system must be able to carry its proportionate fire extinction supply he considers (p. 202) that the minimum size permissible should be 5 inches instead of 4 inches as allowed usually in England; in America the minimum diameter is often 6 inches, and 8 inches has there been suggested for it. The more a town can afford for its fire extinction service, the better.

280. Hydrants.

(*a*) *General Remarks.*—Hydrants must be sufficiently numerous, and must be so placed as to be able to furnish the fire streams contemplated. Generally, the intersections of two streets are good situations for them, so that they can be used in four directions; in this matter it is best to locate them not simply with reference to the distribution map, but also in accordance with the independent ideas of the Fire Brigade authorities, who may be given such a map on which they can indicate the positions selected by them. The more hydrants provided the better, but naturally the expense involved has to be considered. In thickly populated parts of a town, and especially in its business quarters, the spacing of hydrants should not exceed 100 yards, and in other parts 150 yards; where street intersections are more than 150 yards apart, there should be at least one hydrant intermediate between each. The pipes must be able to give a full supply at the same time to all the hydrants on each section of them; the pipes should be fed from both ends by the mains, which is equivalent to doubling their number and discharge with the same head, or to giving the same discharge as if they were fed from only one end, but at about one-fourth the loss of head. Where a large number of fire streams has to be concentrated, hydrants may be replaced by fire cisterns supplied by large pipes, so that several connections may be made with them.

(*b*) *Requirements for Hydrants.*—The requirements of a good hydrant are that it must—

Give a full, unobstructed flow;
Not leak, stick, freeze, or get out of order;
Allow hose to be easily connected with it;
Be inexpensive.

It is advisable to select forms which have a proved efficiency; only a few little tried new patterns should, if desired, be purchased at first for experimental purposes; the simpler they are the better. Hydrants should have ample waterways without sharp angles and sudden changes of size. They may be fitted, so as to take one, two, or three connections, and should be fixed to branches of diameter sufficient to give full supply to all at the same time; each of these should be controlled by a valve where it takes off and should be laid as deep as the supplying main as a protection against frost. The internal diameter of hydrants was originally 2½ inches, but now one of 3½ inches is preferred, so that two hoses may be fixed to each of them. The usual diameter for a hose to enable it to be handled easily is 2½ inches; with this a good jet can be thrown from a 1-inch nozzle, a fair one from a

1⅛-inch, and a poor one from a 1¼-inch diameter nozzle. All nozzles should be standardised.

To prevent pillar hydrants from freezing, they have been fitted with frost cases in cold countries. The danger from frost in all hydrants is that normally the internal tubes remain full of water, which on freezing will expand and cause breakage. To obviate this the tube is drained by a small drain-pipe closed by a valve which is opened either by hand or, better, automatically, by a " clack " valve (which comes into action when the main sluice valve is closed); the drainage water can be passed into a sewer.

(*c*) *Forms of Hydrants.*—There are many forms of hydrants, and these are illustrated in makers' catalogues. There are two main classes—" pillar " hydrants and " sunk " hydrants. Of these there are various types—" ball," " sluice valve " and " screw down " hydrants; the first kind has the valve at the base of the pillar, and the two last have theirs fixed in short tee pieces upstream of the standards, and forming part of the fixed castings; these parts should be removable without digging up the hydrant seating.

(i) Pillar hydrants have a vertical pillar projecting about 3 feet above the pavement, and with the hose connections near the top; they are generally fixed on the outside of the side walk. They are thus conspicuous and immediately ready for use, but are not much employed in England because of their expense, and presumably because they are considered to be in the way of traffic, although this latter objection is not a strong one; in America they appear to be favoured.

(ii) Sunk hydrants are fixed below road-pavement level, and have a hinged cover at that level. To enable their positions to be ascertained when the covers are under mud or snow, reference tablets are inserted in the nearest walls, giving their distances therefrom. When this form has to be brought into use the cover is opened, and a short stout copper stand pipe with hose connection is fixed to the hydrant, and this entails extra trouble and delay. A modification of the ordinary type has two short telescopic pipes with hose connections, the tops of which are normally below street level; when the hoses have to be attached these telescopic pipes are raised so that their tops are above that level. The cost of this form is unfortunately high.

(iii) Ball hydrants have for valves rubber-covered balls, which are actuated by means of spindles passing axially up the stand pipes and terminating at their tops in capstan heads, which are screwed down by handles to close the valves. This type is more liable to leakage than others, as dirt lodges between the ball and its seating, and the ball itself may become grooved or distorted under pressure due to heads of from 100 to 150 feet; with lower pressures this form is satisfactory, and it is cheap.

(iv) Sluice valve hydrants are the standard waterworks pattern used in England, where the water is filtered. The valve (Fig. 154, p 643) is a vertical hollow, slightly tapered gun metal or brass disc, which when closed fits water-tight on to inclined annular seatings on each side; when being opened it travels up a screwed spindle fixed axially in the tee branch, which has a stuffing box at top, and the spindle is rotated by a capstan key. This form is not suitable for unfiltered water, as grit is likely to abrade the sluice and its seatings, and thus to render the hydrant not perfectly water-tight.

(v) Screw-down hydrants are commonly used in America, where, on account of unfiltered water being supplied, the valves are made of sole leather or india-rubber and seat on brass; in England the valves may work "brass to brass." The valve is a circular horizontal disc, which when closed fits on to an annular seating. Attached to the valve is a stout spindle cut at its base with a screw thread, which engages with a brass female screw block fixed in the main casting, passes through an annular guide and a stuffing box formed in a tee branch from that casting, and is finished off with a key head, which is actuated by a waterworks key handle.

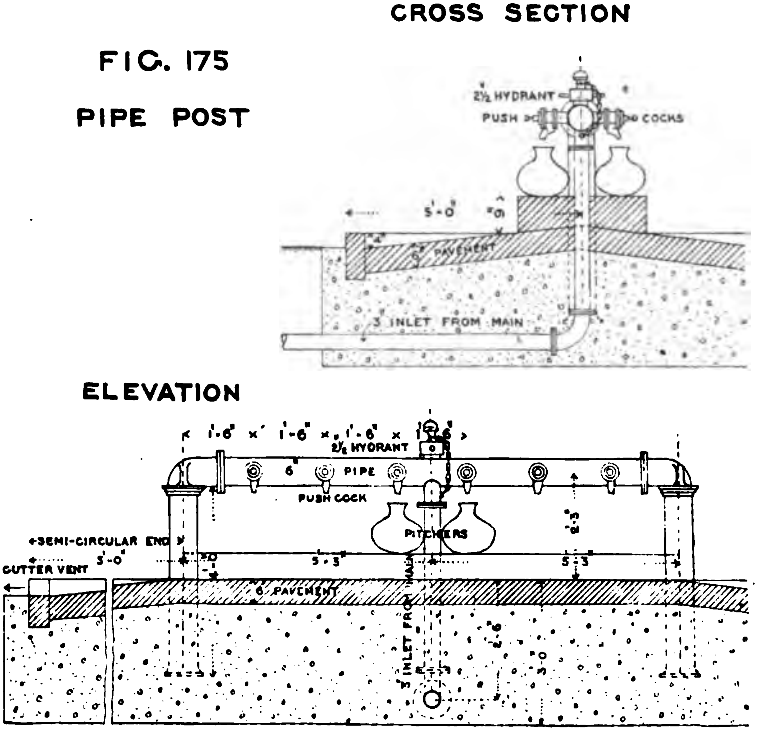
281. Appliances.

Besides the pipes and hydrants, the distribution system may include fountains and drinking taps and troughs; various valves may be necessary—air and scour valves (unless the hydrants are made to serve for these), reflux, safety, and stop valves, which are similar to those described for the supply main (Art. 265); also meters and service connections.

(*a*) *Pipe Posts and Distributing Cisterns.*—In the smaller Indian towns water is not laid on to the poorer class of houses, and the inhabitants thereof get their supply from street services. Fig. 175 shows a "pipe post" for filling twelve pitchers at once from push-cock taps, which close when pressure on their heads is released; the objection to this form is that the gurglitation of the water in the pipe due to its abstraction by numerous outlets diminishes the rate of discharge in each. Fig. 176 shows a design for a "distribution cistern" intended to obviate this; the supply from the main passes into a closed 4 feet × 4 feet × 4 feet wrought-iron cistern through an inlet pipe, with an air valve at top, and is deliverable to sixteen pitchers by small pipes fitted with push cocks branching off from distribution pipes laid below the cistern; all these pipes are straight, so that they can easily be cleaned. The space between the iron cistern and the enclosing outer walling will, if filled with air, act as a non-conductor. It can, if desired, be filled with sand, so that the former may receive support from the latter, which, however, should not be necessary; this sand can be removed through outlet pipes when the cistern

FIG. 175

PIPE POST

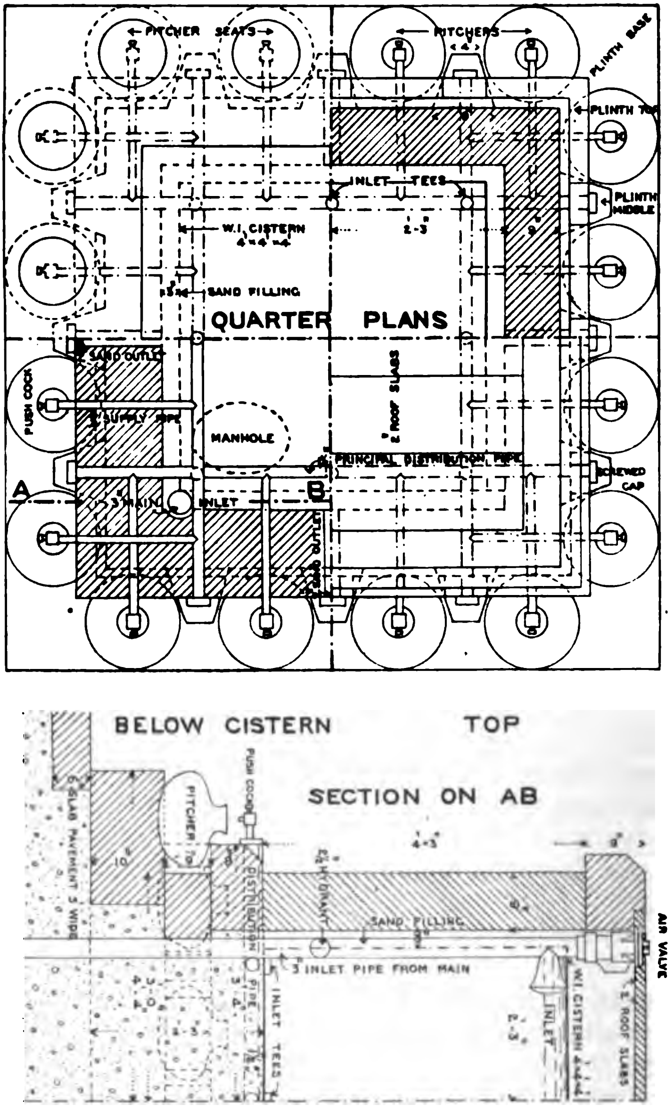

CROSS SECTION

ELEVATION

FIG. 176

DISTRIBUTION CISTERN

FOUNDATION THROUGH CISTERN



has to be lifted out for cleaning and painting. A design for thirty-two pitchers had a 6 feet × 6 feet (mean) × 6 feet cistern formed of masonry walling battering internally and arched over; the inlet supply was controlled by a ball cock, and the outlet arrangements were similar to those just described. Another design for eight pitchers had a 2 feet 6 inches diameter and 3 feet high closed cast-iron cistern enclosed in masonry walling and fitted with radial distribution pipes; in other respects it was similar to the first described cistern.

(*b*) *District Meters.*—For the installation of district meters (Art. 248 (*f*)) the town is divided into a convenient number of districts, each of which may have a population of from 2,000 to 3,000; in each of them a district meter is fixed, and through that the whole supply is passed and measured, the rate of issue being recorded on a ruled and graduated diagram fixed to a revolving drum actuated by clockwork. The best-known meter is that invented by Mr. G. F. Deacon, which, although not accurate enough for the measurement of water for sale, is sufficiently so for detecting waste, and enables this to be done hour by hour. A diagram for twenty-four hours is first taken for each meter, and this by its record of consumption during the night indicates the total rate of wastage which constantly occurs. The diagram is again fixed in the meter, and the inspecting staff make a round of the district at night time, sounding each stopcock with the turning key as with a stethoscope; any stopcock through which water is heard to be running is shut off, its situation is marked by chalk, and its number and time of closure are noted; the effect of the closure of these is instantaneously recorded by the meter, to which the inspector has not access. If after closing a stopcock the sound continues, it is due to waste between the stopcock and the main, or from the main itself. If the latter is the case, the sound is generally heard at several stopcocks, and by its relative loudness at each an approximation to the position of the leak is made. The footway and the carriageway are then sounded until the place of maximum noise is located. This is marked on the spot, and next day the day inspector and his men open the ground there, and generally find the cause easily—a burst pipe or ferrule—and repair the leakage. Having completed his round, the night inspector closes the district meter for a minute or two, and then reopens all the closed stopcocks.

The second meter diagram below the first one clearly indicates the amount of wastage temporarily cut off. The most wasteful districts are first taken in hand and put right. Further tests are thereafter made by closing all stopcocks at night, and on the return journey they are opened one by one and sounded; this results in magnifying the sound due to leaks caused by defective ball cocks, etc., of the house services. The houses concerned are subsequently visited, their fittings are examined, and notices for repairs or renewals necessary are issued.

(*c*) *Consumers' Meters.*—These (Art. 248 (*f*)) are of two kinds—"positive" and "inferential." In a positive meter a measuring vessel is filled by the supply water, and thereafter emptied, and the number of fillings is recorded on a register. The meter is exact in its measurement, whether the flow is slow or rapid, but its size is large and its cost great; moreover, some types are apt to cause back pressure in working, and even to stick, and thus stop the discharge.

In an inferential meter a vane is caused to rotate by the velocity of the supply water, and the number of revolutions is recorded by a register, from which the amount of flow is inferred. The meter will measure water with sufficient exactness for all practical purposes—that is, within from 1 to 2 per cent. of the real discharge—as long as the flow is not very small. When, however, the water dribbles past, either owing to a small amount of wastage or to the slow filling of the house cistern through the ball valve, the meter does not measure it fully. This type is of a small size and cost, and does not cause back pressure unless overworked.

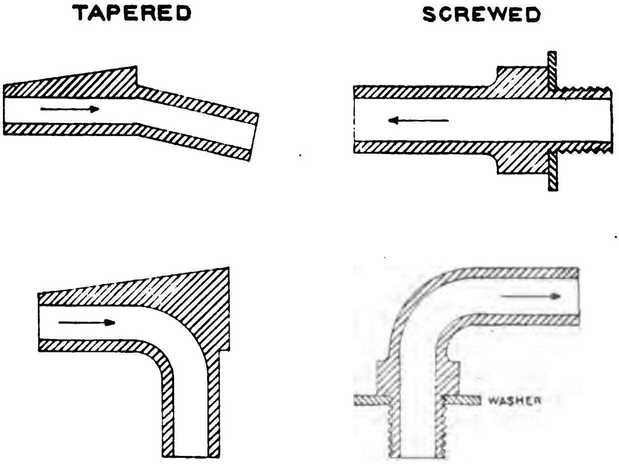
The cost of providing meters to all houses is great, and may amount to a large fraction of that of the distribution system; it will be at a maximum when the population is chiefly located in small houses each containing a few people, and at a minimum when the numbers or quantity served through one meter are large. A meter should work noiselessly, as the house service pipes act as conductors of sound.

(*d*) *Service Pipes and Connections.*—Service pipes are usually made of lead, for coated iron pipes of the small diameter required (from ¾ to 1 inch) are liable to be choked soon by incrustation, sediment, etc. The objection to lead is that it is liable to be attacked and dissolved by certain waters, containing carbonic acid or oxygen, thus rendering them dangerous for drinking; it cannot always be foreseen what action an untried water will have. Lead[1] is removed from the moorland water supplied to Sheffield by mixing with it from 1 to 2 grains per gallon of levigated chalk (Paris white) according to the state of the water. Other waters deposit carbonate of lime, which forms a protective coating, but one that reduces the diameter of the bore. Moreover, lead is expensive and heavy for high pressures. Despite these disadvantages, it is the metal most commonly used; it has the advantages of being practically indestructible, and of being easily bent into any required form or direction. Other kinds of service pipes are made of tin-lined, lead-lined, cement-lined, or galvanised iron pipe; the first is the best, but is expensive; the last is cheap and light, but is apt to rust at the screwed couplings where the galvanising has been cut through at the thread.

The connection between the cast-iron main and the lead service pipe is made by a brass ferrule, which may either be tapered and smooth or cylindrical and screwed (Fig. 177), and this fits into a hole suitably bored in the main to receive it. The driving in of the tapered ferrule may crack the main

FIG. 177

FERRULE CONNECTIONS


TAPERED

SCREWED

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[1] Minutes of Proceedings, Inst.C.E., Vol. CLXXXI, p. 8.

and tapping of the ferrule may loosen it when the water pressure will blow it out; possibly the vibrations due to heavy traffic overhead may have the same effect. Screwed ferrules are therefore generally preferred; they are tinned at the outer end so that the lead pipe may be fixed to them by a wiped joint; to save soldering the end of the lead pipe it may be opened out as a trumpet mouth, and a jointing nut screwed home to make the joint water-tight. If settlement of the main is feared, the service pipe may be made with a short U-shaped bend near the connection, so as to give to, and not be broken by, such settlement.

When a main is being laid ferrules are inserted where it is certain connections will be required. Other connections will have to be made subsequently, and this can be done by machines which will tap the main while it is under water pressure and insert the ferrule without causing leakage. It is not advisable to tap the principal mains for service connections; such should lead from small mains laid parallel to the large ones for the supply of the streets concerned. Before the service pipe enters a house a stopcock should be placed to enable the pipe to be shut off during repairs.

282. Maintenance and Repairs.

Maintenance and repairs have been defined in Article 111 in regard to canals; their efficient and continuous execution are much more important in the case of waterworks, as the supply of drinking water must not be interrupted nor seriously diminished, nor left unpurified for a single day. To ensure proper working a capable permanent works establishment must be employed throughout the year, and temporary works gangs as required; on schemes of any size these must be supervised constantly by an inspecting staff. The supply delivered should be gauged daily and recorded at the principal points of issue—the storage reservoir or other headworks, the filters, the pumping station, and the service reservoir—and should be analysed as frequently as possible at most of these points, especially when water-borne diseases are likely to happen or have occurred, so that the preventive or remedial measures necessary may at once be taken to avoid or speedily terminate an outbreak. All structures and parts of the system must be maintained in sound repair, and all waterways and basins kept perfectly clean. Some of the principal measures to be taken are noted below:

Storage Reservoirs—see Article 96.
Gathering grounds and intakes—constant sanitary inspection (Art. 251 (*b*)).
Filters—work and clean (Art. 255 (*f*) and (*g*)).
,, bacteriological and other examinations (Art. 255 (*h*)).
Supply Line—Channels, see Article 111.
,, Masonry Aqueducts—scrape and clean once or twice yearly.
,, Mains—scrape, examine sluices and valves, especially air valves.
,, All kinds—scour sediment out of aqueduct, attend to cross-drainage works, repair bursts and damages, test for leakage and make defective parts staunch, adjust supply to demands continuously.

Pumping Station—maintain machinery, repair masonry works.
Rising main—stop water hammer (Art. 261 (*b*)), scrape main (Art. 263 (*c*)).
Service Reservoirs, etc.—clean out occasionally, repair masonry, attend to pipes and valves.
Distribution—scrape and scour out pipes, flush dead ends; prevent waste (Art. 248 (*f*)); examine and keep in repair all hydrants and valves; adjust connections to suit alterations in demand, maintain distribution map and register of consumption.

PART III. DISTRICT ROADS.

CHAPTER XXIV.

THE ROADWAY.

283. General Remarks.

It is to the development of communications that the rapid progress of civilisation in modern times is due. Railways have rendered land communications easy and quick, steamships have united distant countries by shortening the time of travel by water, and now the conquest of the air promises further to abridge distance.

Telegraphy—ordinary, wireless, and telephonic—may in this light be considered means of mental communication, but without improved physical communication would have their value much discounted. By all these methods of communication mankind has been brought into closer contact, and mind has been enabled to act on mind in a way previously impossible, so that engineering in its broad aspect may be said to be the foundation of modern progress, as is evidenced by the fact that the development of the former has always preceded that of the latter.

The function of roads is a humbler one than those of the other forms of communication mentioned, as it is concerned chiefly with meeting local wants, but for that reason is of great importance, as roads are daily used directly by the whole population, and not at intervals only by part of it, or indirectly by the general community, as is the case with those other forms. The proper design and construction of roads benefit the local population directly, and thus the whole country indirectly, by facilitating local travel and traffic. The greatest development of their utility has been attained only recently in consequence of the introduction of the quick-moving motor, which rapidly deteriorates the old forms of road surface.

Naturally, the most improved forms of road construction are adopted in urban areas, but these are not dealt with in detail here, as this and the following chapter are practically limited to matters in connection with district roads where only ordinary forms of construction are financially practicable and justifiable. Some notes on "tar-bound" roads are given in Chapter XXV (Arts. 316-320).

It is, of course, a truism to say that a road is intended for traffic, but the fact is mentioned in order to point out that the conditions most suitable for the road are opposed to those for the traffic. A direct alignment and easy gradients are likely to be most expensive, but will expedite and cheapen traffic; a highly-curved cross-section will best preserve the surface from damage by rainfall, but will be inconvenient for traffic; a hard surface will make the road more permanent, but is likely to wear roughly, and thus to incommode traffic. It is therefore often necessary to compromise between these conflicting interests, and the compromise should, as far as practicable, be on the side of the traffic, as that deserves the most consideration.

The essential matters of construction for a good road are —(i) Perfect drainage, (ii) solid but elastic foundations, and (iii) a compact, impervious, and durable surface.

284. Classes of Roads.

District roads may be classified in regard to their general character as—

Through or main line roads.
Branch roads.
Feeder roads.

Through roads may be defined as ones of considerable length passing through more than one district, and having important towns as termini. The general alignment of a through road will often be most suitable for a railway, and as the communications of a country are developed, the latter may take the place of the former, and thus greatly diminish its importance by limiting the extent of the travel thereon to distances for which road transit will remain cheaper, speedier, and more convenient. When this development has taken place, the character of the main road will naturally suffer, as less can be justifiably spent on its maintenance. The general alignment and works having already been constructed, will be preserved, but the width and class of the surfacing may have to be reduced.

A branch road is one which connects an important isolated town or a divergent valley with the general line of through traffic. Railway development will in such cases probably be delayed, but may eventually take place. In setting out new main line and branch roads this eventuality should be borne in mind, and as far as practicable their alignments should be such as can hereafter be utilised for railways, and, particularly, important cross-drainage works should be designed, so that they can carry, or be modified to carry, the heavier traffic when the change is made.

A feeder road is one subsidiary not to a main line road, but to a railway, port, or other connection with long-distance communication. When a railway takes the place of a main road, the road traffic conditions will be altered, and feeder roads more or less at right angles to the railway will be required to enable that to deal with a large area on each side of it. If a feeder road is of some length or serves important interests, it may in its turn be superseded by a feeder railway, and its alignment and cross-drainage works should be constructed with this in view.

District roads may be classified in respect of their construction as—

First class—raised, bridged, and metalled.
Second class—raised, bridged, but not metalled.
Third class—neither raised not metalled, but sometimes with cross-drainage works over the more important or difficult streams.

The nature and importance of the traffic to be served will determine the class of road to be adopted.

The general character—alignment, gradients, cross-drainage works, etc.—should be preserved throughout a road, but should be improved, usually by an increase of width and superior surface, in the neighbourhood of large towns, as there it will benefit the heavier traffic and the larger numbers of those who use it.

285. Projects.

(*a*) *Survey.*—A preliminary reconnaissance should first be made to determine the generally best alignment; the ruling points on which the gradients will depend, such as the crossings of hill spurs and watercourses; the places from which can be obtained the materials required for construction; and to ascertain matters, such as the nature of the climatic conditions and of the materials available, which may influence the final decision as to what should be done. Information should be obtained as to the amount and character of the traffic which is likely to use the road, and the seasons when it will be heaviest and lightest; also as to particular requirements which the road should meet. Where there is any doubt as to the proper crossings of leading physical features, cross-sections should be run so as to include all points practicable.

After the alignment has thus roughly been determined, the detailed survey should be carried out. This will include the final alignment and its longitudinal section, the survey and sections of principal cross-drainages and spurs, cross-sections of side-long ground, the fixing of the chief natural objects near the line, the taking of the bearings of prominent distant features, such as hill peaks and spurs, and the determination of the positions and distances of quarries for materials. The nature of the soil, and, where practicable, that of the subsoil, traversed should be noted, and trial pits sunk through it at the intervals required to enable a correct estimate to be framed; in particular, detailed information of this kind should be obtained at all stream crossings, and the trial pits there should be excavated into sound rock, or where this does nor exist, below the probable future foundations to a depth of about 10 feet for important structures, or of 5 feet for smaller ones. The levels of the highest and of ordinary floods should be ascertained for cross-drainages, and for any sections of the line liable to submergence; the flood cross-sections should extend well beyond high-flood level.

(*b*) *Plans.*—These will consist of the following:

Index Plan;
General Plan and Longitudinal Section;
Cross-sections and detailed Surveys;
Drawings of all principal works, and type ones of minor structures.

The Index Plan may conveniently be to the scale of a mile to the inch, and should show all towns and villages within 3 miles of the road, and indicate the direction and distance of principal towns within, say, 15 miles of it; also all roads, railways, canals, and principal existing physical features.

The General Plan, etc., may be to the scales of 8 inches to the mile horizontal, and 20 feet to the inch vertical, and may be divided into sheets of convenient size, with the plan at top and the longitudinal section below. The plan should show the north point, and the sites of all cross-drainage and other works. The longitudinal section should show the natural ground line, the proposed formation line, heights of embankments and depths of cuttings, high-flood and inundation levels, gradients, sites of works corresponding with the plan, existing lines of communications crossed, and permanent benchmarks (these should be fixed as frequently as practicable).

The Cross-sections and detailed Surveys should be plotted to scales which will permit the amount of detail on them to be indicated clearly, and the plans of the works similarly but to natural, undistorted scales. (See Art. 60 (*e*) for general remarks.)

(*c*) *The Estimate.*—The estimate including the Specification, may follow the general lines of Article 61. Provision should be made for all inspection houses required; these should be located at convenient distances apart—about 12 miles—and at sites a little off the road, so as to secure quiet.

286. General Alignment.

The general alignment should aim at connecting the principal intermediate and the terminal towns by the shortest route practicable, with due regard to intervening minor towns and villages, and should also take into account—

The most level course possible;
The best crossings of waterways and ridges;
Nearness of quarries for materials;
The avoidance of land which is of great agricultural value, is costly to acquire, or is swampy or liable to submergence;
The selection of ground which is easy to excavate or will form sound, dry embankments.

Where fairly large towns lie a little off the direct route, it may be desirable to divert the alignment to pass through or nearer to them, and thus avoid the necessity of branch roads to connect them, with the main line. The consideration which should be taken into account in this respect is the reduction to the minimum of the total traffic mileage of the whole system, when that is fully developed by the construction of the road.

The best alignment is one which consists of long straight lengths united by gentle curves, crosses drainage lines as seldom as practicable, and as nearly at right angles as possible, and avoids unnecessary ups and downs. It should suit the requirements of through traffic in general, and of local traffic in particular; thus, as a rule, an arterial line should skirt, not traverse, an urban area where the two kinds of traffic would interfere with each other. In crossing saddles the lowest point should be aimed at so as to reduce the total lift to the minimum. In ascending ghâts, or hill inclines, the road should be kept off steep side-long or precipitous ground for as long as possible, so far as the gradients beyond permit, in order to shorten as much as can be done the length of the expensive and dangerous section of the ascent. Along the lower alignment the number of cross-drainages will be comparatively few, and minor ones easily diverted to major ones; thus the works to carry them under the road will probably not be much more expensive than those for the more numerous runnels with smaller catchments along the upper alignment.

287. Gradients.

The gradients of a road should be regulated by the nature of the traffic it has to carry. In this connection a "ruling gradient" should be settled, that is one which will nowhere be exceeded in steepness, so that full loads may be transported over the whole length, and the necessity may be avoided for reducing them so as to enable the traffic to surmount inclines having a greater rise. The flatter the gradient, the better will it be for traffic, both light and heavy, and the easier for the consolidation of the surface by rolling during construction and repairs. An absolutely level stretch of road extending for a considerable length may, however, introduce difficulties in drainage; it is therefore better to have instead a very gentle gradient, the rise of which will only imperceptibly affect traffic. A rising gradient increases the haulage effort necessary for all kinds of traffic; a falling one diminishes such effort, but if excessive will tend to produce undue acceleration, which tendency has to be resisted by the application of brakes, or of incommoding backward resistance by draught animals. It has been suggested that this tendency should be taken into account when settling the ruling gradient, and that its inclination should be such that a loaded vehicle if left to itself will move downhill with steady, unaccelerated velocity. If this rule is followed, however, the ruling gradient will be steeper for rough than for smooth road surfaces, and this will affect prejudicially uphill traffic, which requires the reverse condition. For district metalled roads a gradient of 1 in 30 is gentle; one of 1 in 25 is fair; one of 1 in 20 is moderately steep; one of 1 in 15 is a hill incline; while one of 1 in 10 is excessively steep, and should be introduced as a limiting slope, and only in special circumstances and for short lengths.

The longer the gradient the more continuous the tax on the strength of draught animals, etc. Where practicable, long gradients should therefore be broken by flats, and their tops and bottoms should be eased for as long lengths as possible. Steep gradients should be short, flat ones may be longer. Not only must individual gradients be considered, but also the whole series of rises, as the traffic has to surmount their total amount. "Switch-backs," i.e. up and down lengths alternating quickly with each other, are particularly trying for traffic, and should be avoided; or, if this cannot be done, should be flattened as much as possible. The least total rise of a road between two points is secured when there are no falling gradients towards the higher of the two, as these have subsequently to be made good by additional ascents. Where heavily-loaded traffic is in one direction only, the flatter gradients should be in that direction, and the steeper inclines in the reverse one. The crests of steep saddles should be cut down as much as is economically practicable, so as to reduce the total amount of lift.

288. Curves.

The curves of a road should also be regulated by the nature of the traffic it has to carry, being made easier when that is fast-moving than when it is of a slow character. Curves are not desirable in the interest of traffic, but are necessitated by the nature of the ground; they should therefore be avoided as much as practicable, but where necessary should be made regular and of as large curvature as possible. They are particularly undesirable on high embankments, near cross-roads and bridges, and on steep inclines, but, unfortunately, have perforce to be more numerous than elsewhere on hilly sections. In such lengths and on steep gradients they should be flattened in longitudinal section (i.e. "compensated") and raised on the outer side in cross-section, but not to an extent inconvenient to ordinary traffic, and the road should be slightly widened so as to assist traffic in negotiating them. Where the traffic is of a rapid kind, the least radius of curve on flat lengths should be 150 feet; where the gradient is steep all traffic will move more slowly, and the radius may be decreased in direct proportion to the longitudinal slope of the road; for slow-moving traffic the radius may be two-thirds of that desirable for quick-moving vehicles. When the line of traffic is not parallel to the roadway, it is an indication that the curve is too abrupt, and that it should be eased; this chiefly occurs on hill inclines.

"Hair-pin" curves, where the road doubles back on itself, are also objectionable; they should be avoided where the slopes of the country are gentle, and permitted only on steep inclines traversing sharp ridges; every precaution should be taken to render them safe for traffic. It is best when the whole length of a curve can be viewed from end to end, but where this cannot be arranged, the length in sight should be as long as possible, especially for quick traffic, so that collisions may be prevented. To gain an unobstructed view along a curve, on its inner side projecting slopes of cuttings should be dressed off, especially at the top, and over-hanging branches of trees trimmed and bushes removed. The ends of the inner side of the cutting should, moreover, not be excavated to entirely straight lines, but should be curved away from the road so as to increase the length of view round the curve; at these ends this can be cheaply done, as the depth of excavation will be small. Heaps of road material should not be stacked where they will interrupt the view along curves.

289. Foundation of Road.

(*a*) *General Remarks.*—A good foundation is a necessity to ensure a good road, for it has to bear the weight of the traffic; in this respect the function of the surfacing is to protect the foundation from wear; with a bad foundation sufficient support will not be given to the surfacing, which will thus break up and cause the foundation itself to deteriorate.

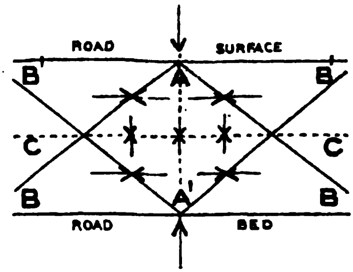
The conditions to be fulfilled by a good foundation are:

- (i) It must throughout be strong enough to resist, without crushing or permanent set, the pressure which may come on it.
- (ii) It must be thick enough to distribute the pressure over such an area of its bed that that in its turn will neither be crushed nor suffer permanent set.
- (iii) It should permit the thorough and early drainage of all surface percolation water.
- (iv) It should be carefully adapted to the nature of the subsoil.

To prevent permanent set a material must not be strained beyond its elastic limit. An elastic material is one that will bend without breaking, and on removal of the force acting on it will return practically to its original position in a short time; a plastic material is one that does not break up under pressure, but on its removal does not return to its original position either early or completely. Thus road surfaces, such as of macadam and stone sets, which have a certain amount of elasticity, require an elastic, or, as it is sometimes called, a flexible, foundation to aid this recovery. Wood pavement, which is liable to crushing, and asphalt, which is plastic, need a solid support like that given by a concrete bed; such pavements should have under them a thin layer of sand to improve their elasticity and drainage.

FIG. 177A

STRESSES ON ROADWAY



(*b*) *Rigid and Elastic Foundations.*—A rigid foundation is bad for a macadamised road; thus, if the metal were placed direct on to a rock foundation, it would not be possible to consolidate it unless it were itself mixed with a considerable amount of resilient material, and even then would soon break up under traffic. Fig. 177A[1] shows what takes place under such a condition; the pressure at any point A on the surface is distributed vertically throughout the underlying road material to an extent indicated by the divergent lines AB.

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[1] Minutes of Proceedings, Inst.C.E., Vol. CLXXVIII (p. 113), "Mallock on Construction of Roads."

If the road bed is rigid, the pressure at A is transmitted vertically to A′, and this sets up corresponding vertical displacements towards the lines A′B′; these displacements of the two opposite forces produced by action and reaction neutralise each other at the central plane CC. At the same time, as the road material is elastic, horizontal displacements due to both sets of forces are set up away from the axis AA′ inside the cone lines AB, A′B′, and by reaction towards the axis AA′ outside these cone lines; the stresses thus tend to expand the material without the cone and to compress that within it. That these actions take place is shown by the dry patch which for a short time surrounds a footprint made on hard wet sand, the dryness being due to the expulsion of the moisture by the pressure of the foot which simultaneously compresses the sand immediately under it, as is also visibly shown by the depression produced.

When between the road surfacing and the rigid base there is a sufficient depth of elastic foundation material, the surface pressure is distributed over a wide area, and the external displacement gradually disappears in the body of the formation. The half angle of the cone BAA′ depends upon the nature of the material, and for ordinary formations lies between 58° and 68°. As the internal stresses decrease from the road surface towards its bed, so should the nature of the supporting formation vary, the material nearer the surface being harder and more elastic than that below it. Were it all equally soft, it would not support the road surfacing, and were it all equally hard, it would be too rigid, and thus in both cases traffic would tend to break up that surfacing. Even if the surface is not actually broken up, a defective foundation causes internal play and consequent abrasion of the particles of metal, thus producing dust which becomes mud in wet weather; as these particles get worn and separated from each other, the percolation from the rainfall on the surface is more readily admitted into the foundation and causes its deterioration. When this internal abrasion is pronounced owing to the badness of the foundation it is not possible to maintain the road surface properly. Moreover, with either a soft or a too rigid foundation the metal moves forward under consolidation by a roller, and thus a corrugated surface is produced. For these reasons a good resilient foundation is necessary to ensure a proper life for the road surface. The foundations of the Roman roads in Britain were several feet thick, and in consequence these highways have lasted well for centuries. Telford specified hand-packed boulders for the layer next the surface in order to distribute the load, but Macadam did not. As boulders are expensive, a thickness of, say, 8 to 12 inches of clean, gritty material rolled in two 4 to 6 inch layers might be substituted for them, and to receive it the top of the road filling of earth might also be rolled to improve its elasticity, solidity, and imperviousness. Naturally, the character of the foundation should be adjusted to the nature of the pressure it has to carry, and should be stronger for heavy traffic and weaker for light traffic. Moreover, it must be adapted to the nature of the subsoil; when that is hard but resilient, the depth of the foundation may be less than it should be when that is rigid (e.g. rocky), or is plastic (e.g. clayey or swampy).

(*c*) *Drainage.*—Good drainage is essential for prolonging the life of a road. The surface should be close jointed, compact, and sloped so as to shed quickly the rainfall which comes on it, and any vacuities that may exist in it should be closed by blindage (Art. 297). The foundation should be of self-draining material, so that it may pass away the percolation water that comes to it. Good side gutters are required to carry off at once all surface water and internal percolation, and should for this purpose be deeper in retentive than in porous soils. Where the ground is soft and liable to hold water, or there are springs, cross-drains may have to be laid under the roadway; these should have a small downstream inclination from its centre towards the side gutters into which they discharge. The object of these arrangements is to secure a dry foundation, for a wet one by capillarity will cause the whole road formation to become moist and yielding, and the surface to deteriorate more rapidly than will result from any other factor of wear.

(*d*) *Construction.*—The ground to be covered by the road should be cleared of bushes and trees, which should be rooted out if they are otherwise likely to sprout; usually grass need not be stripped off nor the surface soil removed. When an embankment rests on steep sidelong ground, the surface should be benched as shown in Fig. 60, p. 270. Drainage arrangements as necessary should be made, and mud, slush, decayed vegetable matter, or material likely to deteriorate, should not be put on the natural foundation. Where the ground is swampy, a layer of self-draining material should be placed on the bed.

290. Embankments and Cuttings.

(*a*) *Embankments.*—The more carefully road embankments are made the better; in this connection the remarks made in Article 139 on canal embankments may be read. As the former have not usually to withstand water pressure and infiltration, they need not be so well constructed as the latter. At the junctions of high banks with bridges, where such action may occur, it is desirable to form the embankment as solidly as possible.

Profiles of poles or bamboos and string should be set out at intervals of about 50 feet so as to indicate the full section after allowing for settlement, which may vary from 1 inch to 2 inches to the foot, according to the nature of the earth used and the way it is formed and consolidated. Generally, the earth from the immediate neighbourhood will be excavated from borrow pits to form the bank. When the natural ground is very soft, the bank should be made of light soils, if these can be obtained cheaply; failing them, the side slopes of the road should be flattened so as to widen the base and thus lessen the intensity of the pressure on it. With ordinary foundations ordinary earth will suffice, but it should be free from mud, slush, decayed refuse, or anything which will cause excessive settlement or lead to water-logging by percolation from the rainfall. Generally, embankments should be avoided, but where the ground is soft and clayey, the formation should be raised about 18 inches above it; elsewhere embankments (which are dangerous for traffic) should not exceed 3 feet in height, except at special places such as near cross-drainage works and across ground liable to submergence.

The embankment should be raised in regular level layers of about 6 inches in thickness, or, better still, dipping slightly to the centre to prevent any tendency of the earthwork to slip outwards. These should be carried right across the full section, and patchings on should not be allowed—in fact, it is better to construct the lower part of the bank about 12 inches wider than the true profile on each side, and to dress off the extra earth when forming the upper part. All lumps and clods should be broken up so as to let the earthwork settle evenly; if consolidation by rolling throughout the section is not to be done, it is best to allow the earthwork to consolidate by settlement during the first rainy season before the metal surfacing is formed, and, anyhow, to roll the top layer (which should be levelled to receive the sub-surfacing) in order to improve its elasticity (Art. 289 (*b*)).

When the slope of a bank has to be made up, the old surface should be carefully benched, and the new material laid of full width without patching in 6 inch layers at right angles to the side slope and rammed or rolled. One chain should be benched ahead, in order that it may be inspected and passed before it is covered by banking. The best material to use for making the new slope is a mixture of half clayey soil and half shaly grit, or a natural soil of similar constitution.

In filling in the approaches of a bridge the earthwork should be brought up level on both sides, and raised simultaneously with the wing walls so as to equalise the pressure on the arching. Similarly, when carrying the embankment over a culvert and filling in the spandrils between arches of bridges, the earthwork should be brought up level and raised with the face walls, so that it may be consolidated by the passage of the labourers over it.

Borrow pits may be excavated for low road banks with their inner edges in the line of the trough of the **V**-shaped roadside gutter (Art. 292 (*b*)), but it is better to retire them a little from it so as not to set up irregular flow in that channel. Where there are catchwater drains the borrow pits may be advanced to them. Within 10 feet of the toe of the road bank there should not be any excavation; at that distance where the bank is high the borrow pits should not be deeper than 1 foot, and their depth may be increased from 15 feet from that toe in vertical steps of 1 foot at horizontal distances of 5 feet, so that they may not be dangerous to out-of-hand vehicles. Borrow pits should not be excavated close together for long lengths, as if this is done irregular channels in them may be formed; at every 100 feet there should be an unexcavated strip 10 feet wide to prevent this.

In the tropics borrow pits in the rainy season form breeding grounds for the Anopheles mosquito, the bearer of malarial fever. As that insect generally does not fly more than 200 yards from its breeding place, it is best not to excavate borrow pits within that distance of houses; where, however, they have to be dug in that limit, they should be filled—if necessary, by rubbish covered with clean dry material. In other places the silting up of the borrow pits should be encouraged by turning the water from gutters, catchwater drains, and field drainage into them.

(*b*) *Cuttings.*—When cutting through high ground it is best to take out the excavation in steps 1 foot by 1 foot between excavated profiles about 50 feet apart, and finally to dress off the projections to the true side slope. Deep cuttings should have their tops sloped back to prevent slips, and the excavation at the ends of curves should be sloped away from the road so as to improve the view along the curve and thus prevent collisions. The formation width at the base of a cutting should provide space on each side for a gutter of sufficient width to discharge the run-off from half the road surface and the whole of one side slope; to facilitate drainage the gutter and roadway should have a gentle gradient extending throughout the cutting, or, in the case of a saddle, small gradients falling on each side from its centre. When the spoil from a cutting cannot be utilised for the formation of neighbouring embankments, it should be placed on low ground close by, so as not to surcharge the high part of the excavation, and formed into neat level spoil banks with tops falling slightly away from the roadway, so as to lessen the run-off of rainfall into the side gutters.

291. Side Slopes and Side Widths.

(*a*) *Side Slopes.*—The slopes to be given to embankments and cuttings will vary with their heights or depths, and with the nature of the soils of which they consist. As usually they will not have to withstand the action of water standing against them, they need not generally be so flat as those noted in Article 117, but they must be sufficiently gentle so as not to induce the formation of slips. Slips are most likely to occur in deep cuttings through shaley or laminated strata, and on the side to which these dip. Special precautions are there necessary, and these usually take the shape of drainage arrangements, as, generally, supporting retaining walls are too expensive to construct unless the land or property cut through is valuable. Good catchwater drains and gutters are required at the top and base of the cutting; the former should be set back a sufficient distance from the top edge, say, equal to from half to the whole depth of the excavation according to the nature of the strata, but not less than 5 feet, and the berm thus left should, if practicable, be sloped to the drain, which, if necessary, should be paved. To drain the actual slope of the cutting surface, drains are often made, either at right angles to the line of the road, to divide that slope into more or less independent sections, or diagonally down it to intercept and pass off the drainage at short intervals. In really bad cases it would be best to excavate the slope as a series of terraces with a longitudinal gradient parallel to that of the road and a cross-sectional fall to the hill side where gutters, paved if necessary, would be formed. The cross-sectional areas of all drains must be sufficient to carry the greatest discharge possible, so that there may be no spill from them, and these areas must accordingly be made in proportion to the amount of the drainage water flowing in the drains from point to point on their course.

Where the ground is valuable (e.g. rice lands), or is liable to submergence (e.g. tidal areas), it may be necessary to substitute for the side slopes rough drystone walling on each side of the road, and this and the traffic should be protected from damage by a line of guard stones (Art. 310) fixed inside the walling.

(*b*) *Side Widths.*—Fair general widths for the road surface proper are:

First-class roads	18 to 20 feet..
Second-class roads	16 feet.
Third-class roads	12 feet.

The widths adopted in any case must be in proportion to the traffic to be carried; the width of a roadway is an important matter, and the greater it can be made within ordinary limits the better. The widths noted are those required for the general traffic, but in addition it is advisable to have on each side of the central track side widths varying from 3 to 6 feet in width coated with less expensive surfacing. These side widths have the following advantages:

(i) They support the sides of the road metal proper, and prevent it from spreading;

(ii) They virtually increase the width of the roadway and will allow that of the central track to be diminished if necessary;

(iii) They permit the central track to be surfaced and consolidated throughout in one operation, which will make a better roadway than if this were done separately in two half-widths; when these operations are being carried out the traffic can pass temporarily along the side widths.

(iv) They form softer and convenient tracks for light traffic—riders on horses and cycles and foot passengers.

The surface of the side widths should not be made of earth, as that will be muddy in wet weather, dusty in dry weather, and liable to be cut up throughout the year. Soft side widths, moreover, bring mud and dust on to the central metalled width, and thus disintegrate it. The harder the material used for surfacing the side widths the better for traffic throughout the year, and the cheaper for annual maintenance, as a hard side width will last long in good condition and will not require yearly consolidation. For this reason it is advisable to surface them with second-class metal, and to finish that off with a thin coating of sand. Narrow roads in particular require hard side widths.

Where the roadway has to be clearly defined or contracted in width, e.g. at bridge and cross-drainage approaches, high embankments and deep cuttings and in urban limits, the traffic surface should be confined and supported by kerbing laid on a hard grit foundation; to protect this and the traffic at dangerous places there should be inside it a line of guard-stones spaced from 3 to 8 feet apart. Kerbing is necessary where otherwise road-drainage channels would impinge direct on the roadway, especially on hill inclines; the drop outside the kerbing should not exceed 3 inches, so that out-of-hand vehicles may not have difficulty in getting over it back to the road. The minimum width of the kerbing should be 9 inches, and its minimum depth 6 inches; it should consist of the longest stones practicable, so that each may give the maximum resistance to disturbance, and it should be laid on a good dry foundation of muram, quarry spauls, etc.

Proposals have been made to have the roadway divided into tracks reserved respectively at the centre and sides for fast and slow traffic, and also to have for up and down traffic respectively two separate tracks divided from each other by a central footway. These suggestions have not met with much approval on account of the expense they entail; the cheapest efficient arrangement is to have a single roadway as wide as can be afforded, and then the traffic will adjust itself on it.

(c) *Width of Road Property.*—The width of the land to be acquired for a road should provide for—

The roadway proper including side widths;
The slopes of embankments and cuttings;
All drainage arrangements;
Borrow pits and berms for stacking materials;
Roadside plantations.

In addition quarries for roadside materials should be acquired. The limits of such property should be carefully demarcated by boundary stones, and encroachments on them should be guarded against by frequent inspection, especially where the land is valuable.

292. Road Drainage.

(a) *Surface Drainage.*—The necessity for good drainage has been mentioned in Article 289 (c), where the precautions to be taken to lessen the prejudicial effect of internal moisture have chiefly been noted; works for dealing with external run-off will here be described. Artificial watering of the road, if excessive, and rainfall if prolonged and heavy, tend to channel the surface, and, when once this scouring has taken place, it is likely to increase, as it will concentrate subsequent flow along defined lines. Moreover, the channels will remain damp longer than the rest of the road, and will be softer than it, and thus be more likely to be cut up by traffic. If the road camber is very slight, it can be increased somewhat in curvature to shed the rain water normally and evenly, care being taken that thus traffic is not incommoded. If the road is important, side kerbing (which is expensive) can be laid so as to prevent the deepening of the outfalls of the surface scour channels. On less important roads short and very shallow cuts may be made at the side of the metalling to stop the formation of long diagonal scores. It is on hill inclines, where the longitudinal slope is steeper than the camber, that the surface guttering is likely to be most pronounced, and in the tropics to be caused during the rainy season when traffic is at its minimum. There very low ridges of gritty material are placed at intervals across the road to arrest the drainage, and are removed before the fair weather comes; in plan they should be made of a flat V-shape, with the apex pointing uphill and on the centre line, so as to divert the run-off to each side of the road when that has an ordinary camber. A better arrangement is to divide the gradient into sections, each division being made by a very short length of flat, with a slight fall to the uphill side, so as to catch the water and pass it off to the side of the road.

When the surface is moist it is softer than when it is dry. As evaporation is slow in temperate climates, it is advisable there to trim high hedges low in order to let the wind sweep across the road, and not to have a continuous roadside avenue, so that the sun may have a chance of drying the road. In the tropics low hedges are advantageous, as tall ones are weak. As continuous shade is there a comfort, all that is necessary in this respect is to trim off the lower branches of trees to about 12 feet from road-surface level, as the naturally high temperature will induce evaporation.

(*b*) *Gutters.*—Gutters are not required where the road is in bank over 1 foot high; there it is much better to let the drainage pass over the ground in a thin film and not as a concentrated discharge. Moreover, gutters below banks may erode their toes and constitute an added danger to traffic. Gutters are necessary where the road is in bank less than 1 foot high, or in cutting, to lead the surface drainage away from it. They should be V-shaped in cross-section, sloping, say, 1 in 3 from the road, so that vehicles leaving that can rejoin it easily, and not get their wheels stuck in the gutter, and so that the drainage may be diverted away from, and not be directed to, the formation of the road. Gutters rectangular in section are dangerous for traffic, and may scour the toe of the formation.

Gutters should be diverted away from the road at the crests and bases of steep gradients, so as to lessen the discharge, and thus prevent erosion downstream of the diversions. Long gutters should be diverted at intervals so as to discharge over the fields at places where they will not do harm, or into parallel and external gutters or drains (which alone should carry large volumes), or into natural cross-drainage lines.

The scouring of the beds of long gutters with a large or rapid discharge should, when necessary, be prevented by the construction across them of curtain walls of dry rubble, boulders, etc., the tops of which should also slope away from the road. All obstructions in a gutter which will deflect drainage on to the road should be removed. Where a large gutter has to be allowed next the road its bed must be sloped away from that, and, when necessary, the toe of the bank should be pitched, or in bad cases protected by a low toe wall.

(*c*) *Catchwater Drains.*—These should be excavated where much land drainage has to be intercepted; where they are required to receive the discharge of sections of gutters which if not thus divided up would be very long, and have large flows next the road itself; or where the road foundation has to be drained on account of subsoil water. They should not be close to the road, and should be outside the lines of the roadside avenues; they should everywhere contain their high-flood discharge, and should not breach nor spill against the road bank. Their beds should be sloped away from the roadside, and be protected by curtain walls across them where necessary. The drains (and also the road gutters) should be led into natural cross-drainage lines some feet away from the toe of the road bank; their outfalls should be maintained unobstructed and should meet those lines with tangential curves, so as not to cause obstruction to the main discharges, and, where necessary, should be protected by curtain or tail walls to prevent the beds from cutting back.

293. Road Crossings.

Road crossings are places at which collisions may occur, especially when the traffic is fast. It should be a "rule of the road" that traffic over a main line should have precedence over that on a cross line, and notice boards at crossings should indicate which line of traffic has to give way to the other. At crossings it is necessary that there should be an uninterrupted view for some distance along all the four roads concerned. There for this purpose hedges should be trimmed low and overhanging branches of trees should be lopped, or better, the trees themselves should be removed. To gain the best view on each side, the branch roads a little away from the crossing should bifurcate as a curved V in plan to meet the main road, and the areas between the bifurcations should be left clear of obstructions, and have the signpost fixed centrally between the ends of one pair near the main road.

294. Road Surface—General Remarks.

Metalled roads may be classed as (i) Water-bound and (ii) Tar-bound; in both the body is of metal, the difference consists in the matrix or cementing material. Tar-bound roads are discussed in Articles 316 to 320, while water-bound roads are dealt with here.

Naturally, water in itself has no binding power; its result lies in the effect it produces on the blindage which is added to the surface of the metal to increase its coherence. An excess of wetness makes the road soft, and lubricates the particles of the surface, thus tending to cause them to move about under traffic, while an absence of it renders that friable; both these conditions are injurious and should be avoided. A small amount of moisture makes the surface elastic, thus enabling it to resist the wear and tear of traffic; endeavour should therefore be made to maintain the surface damp. This has been attempted by certain patented preparations of a deliquescent nature which attract moisture from the air, but they have not had extended use. The difficulty probably is that the hygroscopic salts being in fixed quantity cannot adapt themselves to the varying humidity; either they would make the road surface too wet when there was supersaturation, or not damp enough when there was a deficiency of moisture, while when the air was perfectly dry, as it is for long periods in inland tropical areas, they would be inert. Another way of keeping a road damp is to water it artificially, but thus the surface becomes too wet at first (when the metal is liable to be disturbed by traffic) and too dry before the next watering, and is properly moist only between these stages. Constant watering is therefore rapidly destructive of the surface, and is in fact carried out, not to preserve the road, but to lessen the dust nuisance in towns; it is too expensive a measure for non-urban areas. It is essential that the road surface should be impervious, so that an excessive amount of percolation may not find its way into the sub-surface, the embankment, and the natural foundation, if these will thereby be rendered soft. A certain amount of dampness in the underlying layers, if it does not soften them, is advantageous in dry situations, as by slow capillarity it will keep the surface slightly moist, but care should be taken to avoid an excess of moisture. If the air is humid, or the road is shaded and protected from drying wind, nothing in this respect is necessary. Where roads are exposed to long-continued rain, and are thus kept wet for some time, it is desirable to let the sun and air have free access to them, so as to dry them as early as may be possible. Thus the nature of the subsoil, the humidity of the air, and the amount of exposure to sun and wind, are very important factors determining the length of life of a road.

A road must also be able to withstand abrasion not only on its surface, but also in the interior of the metalling. In a loosely compacted and badly cemented road there is so much play among the particles of metal that they soon become rounded by wear, and thus still less capable of withstanding attrition by traffic. It is in this respect that water-bound surfaces are inferior to tar-bound ones in which the superiority of their cementing material prevents this internal movement. The object to be aimed at in water-bound roads is to secure a mosaic-like surface formed by the close interlocking of the particles of metal, and there should be the minimum of the cementing material, as the condition of that is so liable to change. An ordinarily consolidated road may have from 15 to 20 per cent., and a thoroughly consolidated one 10 per cent., of voids. Abrasion in a short time may reduce the macadam to fine dust by about 40 per cent., and the excess of this after filling the voids comes to the surface as dust. As wear is caused by the motion of the metal under traffic, it is necessary to preserve the continuity of the road surface; therefore, as soon as any holes or ruts with crumbling edges are formed in it, they should at once be repaired, and not allowed to extend. Such repairs are best effected in rainy weather, when the new material can most easily be compacted; failing this, resort must be had to artificial watering, for thorough consolidation of all patchings is essential. Where patchings have to be numerous it is a sign that an entire new surface coating is necessary.

295. Wear of Road.

The wear of a road surface is caused by the action on it of the iron-shod feet of animals, and of the crushing pressure of wheel tires and their grinding rotatory motion combined with friction. It is increased by anything which adds to the haulage effort, and thus becomes more when the surface is rough and the gradient steep than when the conditions are the reverse; also, by high velocities when these make the tires leave the surface at intervals and re-descend on it subsequently with greater impact.

The feet of animals tend to pound and pick up the surface; some, however, deny this and consider that these have a tamping effect and consolidate the road, but this can be only when the metal particles are hit fair and square; the tracks made by draft animals on worn roads are evidence of the effect of their feet on the surface. Modifications of the shoe might lessen that effect just as reverse ones—roughing to give better foothold in frosty weather—increase it, but there must always be pounding and disintegrating action.

Tires wear out the surface by direct crushing, especially if any of the stones project and cause the wheels to ascend and then descend with increased impact; also, by making the stones rub against each other if they are not held tightly in place, or are not in elastic contact with each other, whereby the pressure on them is distributed; thus water-bound roads being inferior in both respects to tar-bound ones, are less durable than they are. When a wheel rests or rolls on a road surface it is in contact with it over a certain area, which must be sufficient to bear the load by elastic reaction; if such area has to be obtained by the depression of the surface, and the deformation is beyond the elastic limit of the roadway, the surface is strained and becomes worn. The mean intensity of pressure between road and wheel is equal to the load divided by the area of contact; with solid tires (iron and rubber) the maximum intensity is one-and-a-half times the mean. With pneumatic tires the pressure is nearly evenly distributed over that area, and the tire is itself compressed under the pressure, thus considerably increasing the area of contact; for both reasons the intensity of stress on the roadway is reduced; a solid rubber tire acts similarly in increasing the area, but less effectively. The mean pressures of the three forms of tire—pneumatic, solid rubber, and iron—are respectively about in the proportion of 1, 2, and 24. The mean pressure of the pneumatic tire depends upon, and is practically equal to, its own air pressure; the less this is the better for the road, but the worse for the tire, owing to the consequently increased wear of its fabric.

The downward velocity from a projection of height h of a tire of radius r, rolling with velocity v, is $v\sqrt{\frac{2h}{r}}$, and thus varies inversely with the square root of its radius; the force of its impact on the projection is $v^2\frac{2h}{r}$, and thus is inversely as its radius. In the case of hard tires, small wheels are therefore more destructive than large ones, but not in that of pneumatic tires, where the intensity of pressure on the road is about the same as that of the air pressure in the tube; with the latter vertical acceleration increases the area of contact, but not the intensity of pressure on the road. Iron tires should therefore be broad, of large diameter, and smooth, so as not to concentrate the pressure on projections. The First International Road Congress (held in Paris in October, 1908) recommended that with the tires now in use the maximum pressure per inch width of tire should be 825 lbs. Traction engines are the most destructive vehicles owing to the large amount of power exerted by the driving wheel. In the Renard train this is not concentrated at the engine, but is distributed by means of a shaft to each of the vans forming the train, and each thus virtually becomes its own tractor.

In America coefficients of the road-damaging effect of various users of roads have been determined, but the determination of different computers varies. The New York State authorities give the following relative figures:

Led or ridden horses and motor cycles—1.
Vehicles with 1, 2, 3, 4, and 6 horses—2½, 3½, 5, 6, and 8.
Motor vehicles: taxis, 4–5-seated-, 6–7-seated-cars, and trucks—2, 4, 7, and 10.

For any given vehicle its destructive effect is proportionately not less than the square of its speed.

In addition to the uniform level wear of a road it also suffers by the corrugation of its surface, and the alternate rises and falls thus produced increase the destructive effect of vehicles on it. This corrugation has been held to be due to:

Inferior foundations;
Variations in the metal of the roadway;

Too thick spreading of the metal before consolidation;
Rolling with too heavy rollers at the start of consolidation;
Poor blindage or binding material;
Inter-attrition of the particles of metal.

Although these may be contributory causes, the determining factors are probably rhythmical vibration combined with friction due to the passage of wheeled traffic. Corrugations are also found on weavers' shuttles, lift guides, overhead trolley wires, and the rails of railways and tramways, all of which are homogeneous, dense, solid bodies, and not made of comparatively variable and loose particles; even plastic asphalt laid on uniform and rigid concrete suffers from corrugation. The faster the traffic, the closer together are the corrugations, and they are thus formed chiefly on steep gradients; the greater the pressure and the harder the materials of the road surface, the more pronounced are the corrugations. There does not appear any way of preventing corrugation except to reduce the speed of the traffic or the hardness of the surface, and both these measures are impracticable. Corrugations have the bad effect of guttering the road surface during heavy rainfall, and preventing the even run-off of the water; the hollows remain damp longer than the ridges, and thus get more cut up; traffic is thereby impeded, and also by having to pass over the succession of rises and depressions which induces the jolting of quick vehicles.

296. Metalling.

A dusty, rutty, or nubbly road is an indication of the coating being too old, of inferior or unsuitable metal having been used, of too early application of blindage, of want of proper consolidation, or, if soft material such as laterite has been used, of its too early consolidation in the rainy season and its subsequent churning up. Too thick a coating makes a road hard and unyielding, too thin a one will not resist traffic properly.

On new roads a first coating of metal should be laid on the prepared foundation in two layers, each, say, 2½ inches thick at the sides and 4 inches at the crown; the first of these should be lightly consolidated, so that it may key into the second, which should be thoroughly consolidated. Some recommend having on a 6-inch foundation a total thickness of metal of only 6 inches uniformly over the whole road, the first layer being 4 inches and the second 2 inches thick ; others specify a uniform thickness of 9 inches for important roads with heavy traffic ; naturally, the thickness should be in proportion to the nature of the traffic. As traffic tends to keep to the centre of a road, the larger particles of metal should be placed there, and the depth of the metalling should be increased to withstand the greater amount of wear probable.

On old roads, before a fresh coating is added, the thickness of the existing coating should be ascertained by digging small trial pits through it at intervals. If that exceeds 10 inches at the crown, the metalling should simply be picked up, barrelled, and rolled. This prior determination of the existing thickness of the metal is especially necessary at bridges, etc., so as to obviate their being over-loaded by a too thick and heavy coating. The defective particles of old metal, i.e. those which are too small or too much abraded for use in the centre of the road, should be utilised for remaking the side widths. If the old road had no foundation, but the subsoil is dry and not of a retentive nature, it will seldom be necessary to provide during its repair for a pitched or hand-set foundation of large stones ; all that will then be necessary will be to add a new coat to the old surface, which should be picked up for the purpose. If, however, the subsoil is heavy and subject to flooding, reconstruction with proper materials is advisable.

Frequently re-metalling is done separately on two half-widths, but this usually results in a longitudinal joint along the centre of the road, which is objectionable ; care should be taken to prevent this and to complete the second half as soon as possible after the first one, so that the two may be under the same conditions of weather and traffic. It is much better to re-make the whole width of the surface in one operation ; to enable this to be done the traffic will have to be diverted temporarily, and this can easily be effected if side widths are provided (Art. 291 (*b*)). At the ends of the section re-surfaced, care must be taken to slope the new coating evenly on to the neighbouring old surfaces without any abrupt change of level.

Two varieties of metal should not be used in the coating, for if used the wear will be uneven, and the surface will be rendered nubbly by the projection through it of the harder variety. The molar teeth of elephants have vertical alternating bands of hard and soft material in order to obtain more grinding action, and the proper relative height of their surfaces is maintained by organic growth. In a road, wear should be minimised, and, if irregular, the surface will not be automatically made good.

297. Blindage.

Blindage is required to finish off the surface of the metal coating by filling up any interstices which may remain after it is consolidated. These interstices should be as small as possible, and therefore blindage should not be added until the metal particles have been brought into as close contact as practicable, or it will keep wide the spaces between them. Blindage properly applied increases the frictional adherence of the stones, and thus lessens internal abrasion; also, it makes the surface less porous, and thus prevents internal percolation, which injures the foundation of the road. The smaller are the particles of metal the finer should be the blindage, and the less of it should be required. Macadam specified that the metal should be small (to pass through a ring of about 1½-inch diameter), and that the surface should be made without binding material—sand, clay, or road scrapings. Blindage should be—

Coherent, so that it may bind, but not sticky, or it will cause vehicles to lift the metal;
Retentive of moisture, but not pervious, so that it will continue to bind in dry weather;
Hard, but not friable, so that it will not readily grind into dust;
Durable, so that it will not disintegrate and form dust and mud.

In England fine clean gravel is used for blindage, and in parts of India muram, or disintegrated trap rock; granite chips and small hard quarry refuse where available are useful materials. After the blindage is laid, a layer of clean sharp sand ⅛ to ¼ inch thick should be spread on it before it is consolidated, so as to lessen any stickiness there may be, and so as to fill the interstices more completely. Of the total amount of sand provided, half should be used initially, and the balance applied in equal quantities (one-quarter each) at two intervals during the year. Muramed roads should be finished off with a thin coating of sand. An excess of blindage lying above the road metal will grind rapidly into dust. The nature of the blindage should be suited to that of the road metal. Material which easily turns into dust or mud should not be employed; road scrapings are often used as blindage, but this does not appear advisable, for they have already formed dust and mud, and will thus readily produce them again. Blindage applied too early in the rainy season is likely to be churned up on the surface into mud by the traffic; if spread in the dry weather, the traffic will roll it further into the interstices of the metal, where it will be protected from wear, and will better hold the particles of stone.

298. Dust and Mud.

Dust is produced by the crushing of—

The external surface of the metal and blindage;
The internal surfaces of the metal by inter-attrition;
Mud brought on to the road.

That crushing is due to the action of the feet of animals and of the wheels of vehicles, chiefly those with iron tires, as rubber and pneumatic tires have much less, but still some such effect on the road. Pneumatic tires are said to destroy the surface by "suction" due to their elasticity producing a partial vacuum; this, however, does not appear to be the case, as they leave prints of their own surface on a road, if that is even only slightly damp; what displaces the surface material is the striking of it horizontally and backwards by driving wheels, causing horizontal shear. With slow-moving traffic the dust is raised but little, and either falls again on the road or is carried beyond it for only a short distance by the wind, which usually blows at a small angle to the surface, and of course downwards. With quick-moving motor cars the driving wheels stir up the dust, which is then caught by the strong air eddies produced by the body of the car (unless that is designed on lines to prevent this), which carry the particles high up, and they are then distributed widely by the wind, so as to create a great nuisance to marginal property. To lessen such nuisance the formation of dust should be diminished, and the best way to do this is to bind the road surface with tar or bituminous materials. With ordinary macadamised roads the precautions to be taken are to use hard, durable materials, to consolidate the surface thoroughly and with as little blindage as possible, and to remove mud as soon as it appears. One of the sources of mud is the traffic on field roads bringing it on to the main road; this could be lessened by metalling a short length of the former at the junction and keeping that length clean. Allowing the wind to have free access to the road will greatly decrease the amount of material which might otherwise be dispersed widely by quick-moving traffic. Apart from the nuisance it creates, dust has an injurious effect on the road surface, for when dry it increases the attrition by vehicles, and when wet it produces mud. When thick it adds to the haulage effort, and thus to the wear of the vehicles and the stress of their animals.

Mud may either be brought on to the road or be produced on the road by the churning up of the dust when moistened by rainfall. It is disagreeable to foot traffic, and greatly impedes wheeled traffic; it makes the road surface more retentive of moisture and thus more permeable; it lubricates the interior of the metal, and thus causes it to move more freely and wear; and it leads to the choking of drainage channels. By the lessening of dust the quantity of mud will be reduced; where practicable, that which still forms should be removed continuously, so as to increase the life of the road and the comfort of its users.

299. Road Camber.

(*a*) *General Remarks.*—Camber, or barrel, is the name given to the cross-sectional profile of the road surface. It is required solely for the purposes of road drainage, and should therefore vary with the nature of the surface, being made steep for soft, permeable material and flat for that which is hard and impervious. It is not wanted in respect of the traffic, for that is best served by a perfectly flat surface which allows the wheels on each side to bear evenly and for their full width on the roadway. Any inclination of the cross-section tends to make the wheels bear unevenly and for only a portion (on a steep camber for only half) of their width, thus causing them to shear the road and cut into it, while, if the inclination varies from point to point on the section, there is a tendency to set up a cross-strain on the vehicles; the steeper the camber, the more pronounced are these tendencies. As a compromise between these two conflicting interests, the smallest amount of camber which will shed the rainfall should be allowed. This main principle being followed, variations of camber (Fig. 180) as noted below are of less importance, seeing that a very gentle cross-sectional fall is in most cases sufficient to pass off the rainfall speedily. That Figure and the two preceding it are largely distorted to show the effect of the different cambers which they illustrate.

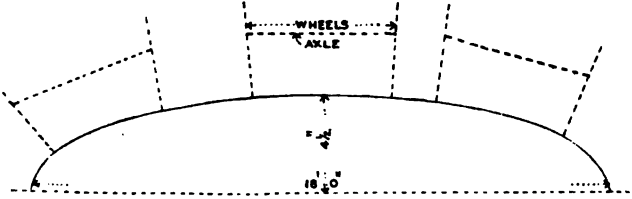
A flat camber distributes the traffic more evenly over the road than does a steep one, but is more liable to suffer from the formation of accidental depressions, and in the case of tar-bound roads, especially in hot weather, to shear towards the sides of the road; a steep camber tends to cause quick vehicles to side-slip. The wider, less permeable, less sheltered, and more important the road and the faster the traffic, the less should be the camber.

In regard to the shedding of the rainfall the rate of inclination of the camber should decrease from the crown of the road to its sides, for as the volume of water to be discharged thus increases, it requires flatter and flatter slopes so as to maintain but not accelerate its velocity. Against this view, advocates of the convex camber hold that as the sides of a road have to discharge more run-off than its centre and remain damper longer, they should have a steeper fall than it; this, however, is true only for a very short time. The amount of camber has to be varied in different circumstances; in moderate inclines it should be increased slightly in order to counteract the tendency there to longitudinal guttering; on steep hill inclines, and especially on curves on them, a single slope from the precipice side to the hill side is desirable to deflect out-of-hand traffic towards the latter.

Before the metal is spread the underlying formation should be brought to the proper profile to receive it, and should be thoroughly consolidated to prevent subsequent distortion of the surface during settlement. Should settlement be anticipated, its amount must be allowed for, so that it may take place regularly, and so that owing to it there may not afterwards be any flattening, much less "dishing" (concave depression), of the final surface. To ensure the correctness of the camber wooden templates of the exact size and shape of the profile should be set out symmetrically with respect to the centre of the road in regard to level and side width, at short distances apart, and the metalling laid truly between them.

(*b*) *Convex Camber.*—The almost universal form of camber is a convex one, and is usually a portion of a flat circular curve (Fig. 178); thus the curvature increases regularly from the centre to the sides, where it is more or less pronounced. As just explained, this is unnecessary for rain-shedding purposes, and it tends to concentrate traffic on the flat crown of the road. A portion of an ellipse, sometimes adopted, is less desirable, as it is too flat at the centre and too steep at the sides. Some consider that with a convex profile the surface acts as an arch, but this is not the case owing to the smallness of the curvature, the irregular character of the material of the roadway, and the nature of the abutments. Naturally, the metalling on each side of a wheel track helps to give lateral support to that immediately under it, but the extent to which the pressure is thus transmitted does not depend upon the curvature of the surface, as that is practically flat, no matter what form of camber is adopted.

FIG. 178 CONVEX CAMBER $\frac{\text{HOR}^{\text{L}}}{\text{VERT}^{\text{L}}} = \frac{1}{8}$

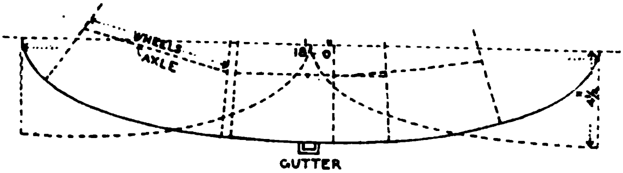


For ordinary district roads, say 18 to 20 feet wide, a total drop of 4½ inches from crown to sides is sufficient, and it should not exceed 6 inches, which is the amount allowed in Ireland for 18-feet roads. Another rule is to have a general gradient of ⅝ inch per foot ($\frac{1}{19}$) for roads less than 20 feet wide, and for wider roads one of ½ inch ($\frac{1}{24}$) to ⅜ inch ($\frac{1}{32}$). For tar-bound roads the drop may be equal to that given by a general cross gradient of $\frac{1}{36}$ to $\frac{1}{40}$; another general gradient is equal to ⅜ inch per foot ($\frac{1}{32}$), and is recommended as the flattest permissible, while another recommendation is one of $\frac{1}{50}$. In

America a fall equal to ¾ inch per foot is usual, but in some cases has been decreased to one of ¼ inch per foot, equal to general gradients of $\frac{1}{16}$ and $\frac{1}{48}$.

(c) *Concave Camber.*—It has been explained in (*a*) above that, looking solely to the shedding of the rainfall, the rate of inclination of the camber should decrease from the crown of the road to its sides. To carry this out the cross-section of the road would be a cusp, with its apex at the centre (as shown by the dotted curves in Fig. 179), which would be an impracticable one for traffic. However, by dividing the cusp in two and starting each half from one side of the road, a concave section results, and this is the origin of the concave camber (shown by the firm line in that Figure) which is recommended by some engineers, and has been constructed by a few. By some it is proposed to have a central rectangular open masonry drain to carry off the drainage, and to cover this by a continuous grating, but this is an expensive arrangement, and would be obstructive to traffic. A better proposal is to pave the centre so as to form a channel, and to drop the discharge at intervals down gullies; in urban areas these would pass it to the sewers; in country districts on side-long ground cross outfalls could be constructed under the road, but where the ground is level in cross-section, and still more in cuttings, a central drain under the road leading to an outfall would be necessary, and that would be expensive. The concave camber thus appears more suitable for urban areas than district ones.

FIG. 179 CONCAVE CAMBER $\frac{\text{HOR}^{\text{L}}}{\text{VERT}^{\text{L}}} = \frac{1}{8}$



The advantages claimed for this profile are:

- It frees the kerbs from mud, and thus prevents the splashing of foot passengers;
- When a central underground drain is constructed, it can be given a gradient independent of that of the road, and the depth of surface flow can be reduced

so that it will not carry enough mud and litter to choke the gullies, as often happens on convex-cambered roads;

As traffic will keep to the centre of the road, side shear at the sides will be small, while that at the centre will be neutralised by the traffic moving there in the opposite direction;

Only one set of gullies, instead of two, is required.

The disadvantages attributed to this profile are:

Its expense, as explained above;

The liability of the choking of the drainage which would flood the centre of the road, the part most used by traffic;

The unsuitability for traffic of gullies, and more especially of a continuous grating, in the centre of the road;

The softening by the central drainage of the part of the road most used by traffic (this is met by the paved central channel);

The road will be deficient in strength (this is on the erroneous assumption that it acts as an arch, (*b*) above);

Heavy, slow-moving traffic, instead of travelling at the sides, will gravitate to the centre of the road to which all vehicles will tend to keep;

The danger to road cleaners getting rid of mud in the centre of the road where the traffic is greatest;

The danger to vehicles turning out of the main into a cross-road of the "cant" being reversed from what it should be.

(*d*) *Sloped Camber.*—This profile is formed of two similar but reversed inclinations at the sides, united by a narrow width of flat curvature at the centre, so as to avoid a knife-edge there (Fig. 180). It has the following advantages:

It reduces the excess velocity of the drainage at the sides, and thus reduces the tendency to guttering;

It is simple to set out and construct;

It provides for an increased thickness of metalling at the centre where the traffic is heaviest;

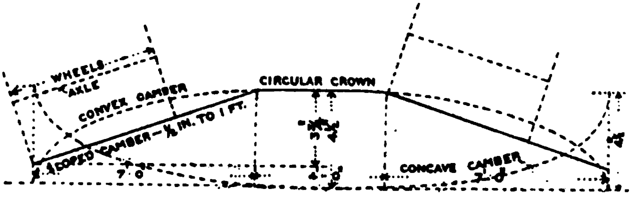
It allows the wheels to bear evenly for their full width on the surface;

It does not tend to produce any cross-strain on vehicles.

For hard metal the camber should have an inclination of 1 in 30; for soft metal, muram, etc., one of 1 in 24. On the whole, it appears to be the most suitable of all cambers and for all ordinary situations.

A development of the sloped profile is to make the whole road surface slope at an even inclination from one side to the other; this, however, would have the disadvantage of passing all the drainage and mud to the lower side, thus interfering with foot traffic there.

FIG. 180 SLOPED CAMBER $\frac{\text{HOR}^{\text{L}}}{\text{VERT}^{\text{L}}} = \frac{1}{8}$



300. Road Metal.

(*a*) *Selection of Metal.*—Metal should be hard, tough, dense, impermeable, weather-resisting, good binding, resistant to attrition and pounding, of uniform character, and suitable to the nature of the traffic; as a rule, fine-grained and heavy stone furnishes the most durable metal. The charge for carriage is generally considered to be a determining factor in regard to the cost of road material, and tends to limit the distance from a road at which a quarry for supply can be worked; in India this limit is taken at about 5 miles for cartage. Carriage is not, however, the chief consideration to be taken into account, for while the rate for it and the cost of laying are practically the same for all varieties of metal, an inferior material will have a shorter life than a superior one, and will entail more frequent renewals of the coating; also during most of its life the road surface will not be so good as that of one constructed of better stone. The proper way is to estimate the cost of maintenance for a number of years in regard to the charges for material delivered on the road side, and for the labour employed in consolidating it. Then, taking into reckoning the life and cost of different descriptions of metal, it can be seen which is the most economical to use, and which, considering the resulting superior surface and the benefit thereby to traffic, can justifiably be used at a moderate increase of expenditure. Or, the annual cost of maintenance with different varieties can be estimated, and the decision as to the one to be selected can similarly be formed. As a rule, the best quality of metal will be found cheapest in the end, and to make the most satisfactory surface; it thus pays to use a high quality stone. The cementing property of stone is of importance; when a stone is deficient in this quality, it should be bound with chips of higher cementing value. In India it is estimated that the annual wear of good metal is 1 cubic yard per mile per cart using the road daily; this gives an idea of the large amount of metal required for maintenance, and of the necessity for careful selection of the stone, for if the wear is greatly increased, the extra quantity wanted will be considerable.

(*b*) *Tests.*—The test recommended for the selection of stone for metal is the attrition test coupled with microscopic examination, as these in capable hands will give a fair idea of the probable resistance to wear. The test should be carried out with wetted stone, for the attrition of dry material is comparatively small. Even thus the test is defective, as it does not reproduce the weathering effect of atmospheric influences, which act deleteriously on all kinds of road material, nor the hammering effect of the iron-shod feet of animals, which is considerable. It corresponds only to the surface and interior wear of loose metal, and therefore exaggerates what takes place when the road surface is properly consolidated; moreover, it does not indicate the cementing value of the material for which a tensile test may be desirable. However, although it does not correctly give quantitative results, it affords qualitative ones, and differentiates varieties according to their relative resistance to wear. Such tests are rarely made in England, and practically never in India. What is chiefly relied upon is the actual experience of the behaviour of the metal on the road itself. For this purpose it is necessary to maintain careful records of the life of metal from different sources, how this was affected by situation and treatment, what maintenance cost resulted, and how traffic was served. Any quarry which produces poor results should be permanently abandoned as soon as possible, and metal should be procured only from approved quarries. The proper system is to combine the practical out-of-door test with the indoor laboratory one, so that full knowledge may be obtained of the behaviour and of the physical nature of the stones used, so as to serve as a guide when selecting new varieties for trial.

(*c*) *Varieties of Stone.*—The following notes refer principally to Indian stones used for metalling:

(i) Boulder trap is hard, free from dust, and durable; it can stand all ordinary traffic, but as it breaks with a conchoidal vitreous fracture, it does not bind well, and makes a somewhat rough, nubbly road; it should therefore be broken small.

(ii) Quarried trap when good is sufficiently hard to resist ordinary traffic, it binds fairly well, and makes a smooth road; the softer it is the better its surface when new, but the shorter its life and the more dusty the road. Good uniform and crystalline varieties should be selected, and irregular or mottled and dull, earthy ones should be rejected.

(iii) Basalts and whinstones have characteristics similar to those of trap rocks.

(iv) Granite, when sound, makes an excellent roadway, but when decomposed is much too friable for use. The syenitic varieties are the best, and the feldspathic and micaceous ones are the worst. Sound gneiss also furnishes good metal.

(v) Quartzite, sandstone, chert, and flint break up quickly under traffic and become dusty; they do not bind, and are too brittle to form a compact road surface.

(vi) Laterite makes a very smooth surface for light traffic, but cannot stand heavy traffic, by which it soon gets churned up in wet weather, and becomes very dusty in dry weather. Under consolidation by rollers the particles coalesce to form a continuous unfissured, and therefore water-tight, surface. If quarried, it should be allowed for as long a time as possible to weather and harden before it is used. Laterite pebbles from river beds are hard, and as they are carried down some distance, this may render practicable an extended use of the material beyond the quarry area. (Ordinary stones from river beds vary much in quality, and should not be used as a rule.) Laterite should be hard, compact, heavy, and of a dark colour. The lighter coloured varieties and those containing much ochreous clay should not be used.

(vii) Ironstone forms a good road for ordinary traffic; its surface is harder but less smooth than that of laterite.

(viii) Kankar (nodular hydraulic limestone) produces a good smooth road for light traffic, but wears rapidly under heavy traffic, and is glaring white under a bright sun. It should be allowed to weather and harden; the best varieties are tough, and have a bluish, almost opalescent fracture and fine texture.

(ix) Limestone binds well and wears uniformly, but as it is soft and gets greasy in wet weather, it is not very suitable for water-bound roads, and then only when the traffic is light. It is a much better material when tar-bound, and its use for such roads is recommended by many for all ordinary traffic.

(x) Second-class metal is a schistose variety of trap; on account of its cheapness it is used for metalling second-class roads, and can advantageously be employed on the side widths of first-class ones.

301. Size of Metal—Blindage—Stacking.

(*a*) *Size of Metal.*—The size of metal should vary with the nature of the stone and the character of the traffic. Generally, large particles are difficult to consolidate, require a good deal of blindage, and form a rough road. Some consider small particles will not carry heavy traffic, but Telford was in favour of ones passing through a 1½-inch ring; with such traffic the stone must be hard and must have a high cementitious value to counteract the tendency of the more numerous particles to increased internal abrasion. As a rule, the smaller the particles, the smoother the road, but the shorter its life; the harder the metal, the smaller should be the particles. On steep gradients, where rolling is difficult, but where a good surface is most necessary for traffic requirements, small-sized metal is desirable. The limits of size generally recommended are such that the particles will pass through rings of 2½ to 1½ inches diameter; laterite particles may be as large as 3 inches ring, but kankar should not exceed 2 inches ring. The largest stones should be placed nearest the crown of the road, where the traffic is greatest. In the case of a new road with its surface formed in two layers, the under one should be of 2½-inch and the upper one of 1½-inch ring.

The shape of the particles should be as nearly cubical as possible, so as to make them bind well, and so as to diminish internal attrition; round or oblong pebbles and angular chips or flakes should not be used. The best metal is that which has been broken by hand, as machine-broken metal is apt to be flaky, and also to have internal fractures, owing to the crushing to which it has been subjected.

(*b*) *Blindage.*—These materials are what are required for finishing off the side widths (Art. 291 (*b*)) and the roadway proper (Art. 297). Gravel should be fine and clean, and should have only so much clayey matter as is necessary to make it bind.

Muram should be sound, hard, clean, and resistant to the weather. The particles (for purely muramed roads) may be as large as will pass through a ring of 3 inches diameter, and should be of the hardest description procurable; soft varieties will not resist traffic, and should only sparingly be used. Muram should not be collected much in advance of the time when it has to be spread, so that it may not deteriorate by weathering.

Sand should be sharp, hard, gritty, and clean, that is, free from earth, soft nodules, and large particles.

All road materials of whatever description should be prepared up to specification at the sites whence they are obtained, and nothing should be brought on to the roadside which cannot be used as it is. Large particles should never be stacked at the roadside, for if stacked they are sure to be spread, and this will make the surface nubbly; besides, if they are stacked there and then rejected, so much carriage of useless material will have been incurred. Extra large metal and muram should be broken up, and inferior stone rejected at the quarry, and sand should be screened of large particles, etc., where it is dug. Like borrow pits (Art. 290, near end of (*a*)), quarries should not be excavated too close to the roadway.

(*c*) *Stacking Road Materials.*—In India, owing to the difficulty in obtaining and moving carriage during the rainy season when the road surface has to be made up, the materials for its repair are not carted at the time of spreading, but are previously stacked at the roadside, where they are measured up and paid for. As metal transactions are extensive and costly, and if not properly systematised lend themselves to the commission of fraud, precautions have to be taken to prevent this. The first is that in any mile stacking and spreading should not go on simultaneously; the whole of the material must be stacked and measured before any of it is spread. The next is to have an easy system of measurement whereby also checking the material at site can rapidly and accurately be performed. The ordinary arrangement is to measure the metal in open wooden frames, say, 5 feet × 5 feet × 13 inches (1 inch extra allowed for settlement), and to arrive at the quantity by counting the number of the heaps, assumed to be each of 25 cubic feet capacity. Even if the stacking is honestly done, it is difficult to be sure afterwards that the heaps are of correct size, and a small alteration of their dimensions may cause a considerable percentage error. Further, the metal in such small quantities is liable to get dirty, especially when being lifted for spreading, to be wasted, and to weather if stacked for a long time. Fraud is, however, easy, as the heaps may be formed on ground with projections taking up metal space, and may not be of full height.

A better plan is to have properly levelled and numbered stacking platforms at intervals of half a furlong, and on them to stack the quantity required for that length of road surface, in regular shaped heaps not less than 2½ feet high. On each side of a milestone the heaps should be of half-size, and one-quarter of a furlong from it, so that each mile may be dealt with independently of its neighbours. If objection is taken on account of the increased lead for spreading, it can be met by having quarter-furlong heaps instead. The platforms should be made at sites where the stacked material will not suffer from traffic, nor in any way impede or endanger that, will not be damaged by floods, etc., and whence it can easily be removed for spreading. Each heap should have its mileage number painted on one of the corner headers demarcating the platform and facing the road. On top of each heap should be a flat stone having its booked contents painted on it; when the heap is drawn upon, its remaining contents should similarly be indicated, so that the balance on the roadside can be checked at any time.

The advantages of this system of material depôts are:

(i) Reduction of the work of measurement, so that that can be undertaken by a superior member of the staff;
(ii) Facility of check by an inspector;
(iii) Accuracy in and fullness of measurement;
(iv) Obtainment at regular intervals of the quantity ordered;

(v) Convenience and safety to traffic by having road material stacked over a minimum area, clear of the roadway;
(vi) Cleanness of the material, especially during spreading;
(vii) Prevention of waste of material during spreading.

The last precaution is to have the metal checked by an independent measurer before it is paid for, and at any other time considered desirable. To prevent collusion the engineer should depute the checker to measure up the heaps in miles or furlongs he himself selects, and should specify the number of heaps to be checked, for which purpose a percentage of the whole supply, say, 10 per cent., might be fixed.

When a new road has to be surfaced in two coats of different sized metal, the material for each should be stacked on opposite sides of the road. Metal for petty repairs might be stacked on the side opposite to that on which metal for renewals is placed, or on the same side in heaps of dimensions different from those of the main supply. Other materials can similarly be stacked; it is convenient for traffic, especially at night time on unlighted roads, if all heaps are formed only on one side of the road.

302. Consolidation.

(*a*) *General Remarks.*—Consolidation of the road surface is necessary to ensure—

Facility of traffic, by the provision of a smooth, regular, clean, and hard track;
Solidity of the road metal, thus lessening internal attrition;
Impermeability, whereby the rainfall is shed rapidly and not allowed to penetrate the road freely.

As previously explained, consolidation to secure these advantages must not be confined to the actual surface, but must be extended to whatever supports it, or otherwise that surface will suffer by the settlement and displacement of its bed and foundation. A rough, irregular, muddy, and soft road greatly increases the cost of haulage and the damage to vehicles; it allows the particles of metal to have free play whereby they grind each other and produce dust and mud; and it permits rain to sodden and soften the substructure. In England the surface of some country roads is formed merely by placing the material in place, and by depending upon the passage of the traffic to consolidate it; during that process the vehicles naturally suffer, the labour of haulage is greatly increased, and the road bed deteriorates. Such primitive consolidation is possible only in a temperate climate, and where gentle rain falls at frequent intervals throughout the year; it would not succeed where the conditions are less favourable, and especially in the tropics, where months of dry weather follow the season of torrential downpours. In regard to consolidation, whatever benefits traffic improves the road and increases the duration of its life. The object to be aimed at is to secure a practically monolithic surface with the particles in elastic contact with each other, so that they may distribute pressure readily to their neighbours, and thus be themselves relieved of an excess intensity of it. No stones should project beyond the general surface—such will concentrate the pressure on themselves, and they will thus tend to work loose, and will, anyhow, increase the haulage effort for traffic.

(*b*) *Rolling.*—Rolling can be carried out on three varieties of surface—

Old surfaces which have become rough by wear—these can be made smooth by re-rolling with heavy rollers after soaking rainfall, and the application of a little sand blindage. In India the process is called "partial rolling," and for it the surface is not picked up.

Re-metalled surfaces—on which fresh metal is added after the old surface has been picked up, so as to receive and bond with the new coating.

New surfaces—which are given their first coating to complete the construction of the roadway.

For re-metalling, the old surface should be picked up 1½ inches deep, preferably in lines across the road; the abraded, loosened stones should be placed on the side widths or stacked in heaps for patching repairs, and the fresh metal, from 1½ to 3 inches in depth, according to the nature of the traffic and the state of the road, placed on the central track and consolidated.

Before new metalling is commenced on a hand-packed stone bottoming, that should be covered with good clean gravel 2 inches thick, so that during consolidation this may be forced into the bottom interstices of the metal in order to cement the particles and hold them together; where the formation is made of gravel, muram, etc., that will itself thus work up. The new metal should be applied in two layers and consolidated (Art. 296).

Rolling should be gentle at first and be carried out by light rollers so as to avoid the formation of corrugations on the loose surface. After all irregularities have been made good, consolidation should be completed by heavy rollers, which should continue to work until they cannot further compress the surface nor bring the particles closer together. The heavy rollers must be able to exert an intensity of pressure greater than that which can be brought to bear on the road by the most heavily loaded tire which will travel on it, so that such a tire may not be able to depress the surface further. Thereafter blindage should be applied (Art. 297).

Consolidation should be carried out early in the rainy season if the metal is hard, and late if it is soft; advantage should be taken of the rainfall, and if that is insufficient it should be supplemented by artificial watering, as a dry surface cannot easily be compacted. Rolling should be commenced at the sides, so as to keep the metal there in place, and should be continued uniformly to the centre. Some recommend that the surface should be rammed before it is rolled; this may be advisable when the metal is large-sized, but generally, as ramming is expensive, slow and difficult to supervise, it should not be done.

Consolidation interferes greatly with traffic; the time taken for it should therefore be reduced as much as practicable. Iron rollers should accordingly be worked "in train," i.e. as many together as possible, one after the other; such trains reduce supervision, and are especially economical when resort has to be had to artificial watering. Consolidation should be carried out on long lengths, so as to get a more uniform surface over some distance, and so as to avoid the loss of time resulting from frequent reversals of the travel of the rollers.

(*c*) *Rollers.*—Stone rollers were formerly used in India, but have been discontinued, as they wear unevenly and are apt to break.

Iron rollers are now the general type in use there. The best pattern is that which has closed ends with arrangements for filling the interior with weighting material (old pickaxes, road metal, etc.); thus the rollers can be made light or heavy as required for preliminary or final rolling. The weight of an empty roller should not be less than three quarters of a ton per foot of its length. An automatic scraper should be fixed on the roller to remove adhering material, which, if allowed to remain, would lift the metal; a strip of wrought iron fixed across the rear of, and with its edge inclined to, the back of the roller is sufficient for this. The roller should be divided vertically into two independent halves on the common axle to enable it to be turned easily.

Steam rollers, being heavier than common rollers, are superior to them, but are much more expensive, and are costly to work. They are particularly useful where—

The rainfall is light and precarious and may have to be supplemented by watering;
Labour and draft animals are scarce and dear;
The metal is large and hard;
" Partial rolling " has to be done;
Consolidation has to be effected quickly.

Motor rollers are useful for the consolidation of patches and in confined situations, such as the roads round buildings. They, however, require specially skilled drivers, and cannot therefore be economically employed in the districts, where, moreover, repairs would be effected with difficulty.

When a roller is out of use, it should be drawn off the road and placed out of the way of traffic, with its pole and collars parallel to the axis of the road. As complete miles are usually rolled at one time, levelled platforms opposite to, or near, milestones and clear of the roadway should be made for the temporary "stabling" of rollers. After the rainy season is finished and no more rolling is required or possible, it is advisable, where practicable, that all rollers in the length concerned should be taken to the nearest storeyard and "parked," i.e. arranged in a straight line outside it, and the poles and collars taken off, marked, and neatly stored under cover. In no case should unattended rollers be left close to the roadside where they would be a danger to traffic. All repairs should be effected well before the rainy season commences, and, thereafter, the rollers should be conveyed to where they are to work during that season. A sufficient number of spare parts should be kept ready in the stores to replace worn out or damaged articles without loss of time.

CHAPTER XXV.

ROAD WORKS.

303. High-Flood Discharge.

(*a*) *General Remarks.*—High-flood discharge has been discussed in connection with irrigation works in Article 52; the remarks therein made apply with equal force to the cross-drainage works of roads. It is true that the failure of a road bridge might not entail loss of life, as that of a reservoir might do, nor loss of crops, which might result from the breaching of a canal, but it would involve loss of money and time, and cause inconvenience to the probably much larger number of people and interests using the road. It should be remembered that the provision for greater discharging capacity does not necessarily lead to a proportionate increase of cost; that provision will usually be made either by enlarging the size of the spans of the work, or by adding to their number, and either of these modifications will probably bring the expensive abutments and wings on to higher ground, and thus make them cheaper.

(*b*) *Allowances for and Observations of Discharge.*—When calculating a flood the actual conditions of the stream must be taken into account, for a tortuous one will not have a flow as rapid as one with a straight course. Although the inclination of the bed may be the same in each case, the irregularity of the current of the former will act as a retarder of its discharge. Hence arises the desirability of straightening the course of a stream at a cross-drainage work. Further, if the stream brings down trees and bushes when it is in flood, the spans must be sufficiently wide and high to pass them as well as the water. Also, if the bed is liable to change, and if the obstruction caused by the cross-drainage work will lead to deposits upstream, an allowance for them must be made. In other words, it should be recollected that a heavy flood does not consist solely of distilled water, but of water charged with floating and sedimentary matters. As roads usually traverse plain country, and themselves facilitate inspection, it should be easier to conduct flood observations for them than for those of irrigation works, which frequently are in out-of-the-way localities. It is most important that such observations should be made continuously on constructed roads, so as to gain information which will be useful in designing works on similarly situated new lines of communication. For instance, on all important bridges there should be engraved the levels of all high floods (Art. 29), both on the upstream and downstream faces of an abutment, or near it on the wing walls, so as to record the afflux and tail levels. When a new cross-drainage work is likely to be built, the correctly known highest flood level should be marked on a header stone securely fixed on one bank, so as to serve as a guide to the provision necessary for waterway, and so as to prevent under-estimation thereof.

(c) *Improvement of Discharging Capacity.*—The waterway of a stream for some distance upstream and downstream of a cross-drainage work should be dressed as uniform as possible to increase the discharging power of that work; all projecting banks should be trimmed off to regular lines, and the earth therefrom used in forming or strengthening the road approaches.

Where the bed is shallow, this clearance may prevent the formation of breach channels upstream of the work. As far as may be a new cross-drainage work should be located where the approach to and exit from it of the waterway are straight and at right angles to it for some distance. Should the stream be oblique or tortuous, it should be straightened for as long lengths as practicable, preferably on the upstream side for a distance at least ten times, and on the downstream side for one of twenty times its width for a small stream, and half these times for a large one. If such straightening is impracticable, the piers and abutments should be built parallel to the stream flow, so as least to obstruct it, and skew arches constructed.

On the beds of some rivers in India cultivators grow swamp plantations in order to arrest silt, and thereby form ground for cultivation. This practice should not be allowed, as it raises the subsoil-water level, which is detrimental to health, and also the high-flood level, not only by the obstruction caused by the deposit, but by the retardation of flow by the plants. It is particularly dangerous near bridges, as it may imperil their safety, and has led to the breaching of their approach embankments. If after the plantations have been removed the silt remains, trenches parallel to the river's course should be cut in it to induce its removal by scour.

(*d*) *High-Flood Level.*—It is not advisable that a new cross-drainage work should be designed so as appreciably to increase the natural high-flood level, as thereby damage may be occasioned to riparian property, the foundations may be subjected to increased scour, and the road approaches to increased pressure and infiltration which may cause them to breach.

It is also not desirable that a road should cross a tributary so near to its outfall into a main stream that the flood-backwater of the latter will extend beyond, or not much downstream of, the cross-drainage work. If the former results occur, that work will have its waterway partly blocked by the backwater and will discharge high floods as if it were a partially submerged orifice If the latter, the backwater will retard the flow of the tributary so that its flood level will be raised, as occurs in the case of a river upstream of a weir (Art. 31). In either case the spans of the cross-drainage work should be made higher, rather than increased in width or number, so as to give them better flood-discharging power. The backwater of the main stream may, moreover, cause the bed of the tributary to silt, and thus further raise its high-flood level.

304. Cross-Drainage Works.

(i) The road approaches to bridges, etc., should be as straight for as long lengths as possible, and sharp curves should be avoided, especially in the case of long steep gradients to level crossings.

(ii) The road approaches on embankments leading to important bridges should have a gentle gradient rising to the bridges and extending from a level "breaching section," say, 3 feet above high-flood level, which will come into action during abnormal floods, and thus save the bridges from being overtopped thereby. The breaching sections should be as long as possible, and should be located some little distance from the bridges, where the embankment is low and the natural ground hard, so as to prevent the formation of deep scour channels should they come into flow.

(iii) All wing walls should be backed for nearly their full height with large dry material at least 1½ feet thick, and this should be backed with fine dry material to prevent the inflow of earth, which would in time make the former impervious. When this is done weep holes are required only near the base, and not at intervals throughout the height of the walls, where their drainage may discolour the masonry. Below the weep holes the filling should be of well-rammed water-tight material. Where existing wings are bulging from the pressure of wet backing, trenches should be dug behind them, and should similarly be filled with dry material.

(iv) The space above the masonry filling of the spandrils of arches of new bridges should be filled with dry material, so as to collect the water percolating from the road surface, and this should be let out of the arch rings by pipes fixed above the middle of the length of the piers.

(v) Drainage vents through parapet walls lead to the discoloration of the face of the masonry by mud washes, especially on laterite roads. Such vents are not required for short bridges, as the road drainage can be passed by the gutters beyond the works. For long bridges the vents should be placed above the crowns of the arches, and should lead to small masonry shoots with "throats" cut below their ends, or to short discharge pipes through the parapet walls.

(vi) The numbers of cross-drainage works should be painted or engraved on the ends of the left-hand parapet walls on each side of the works (as seen when approaching them), and not on the centre of the length of the parapet walls.

(vii) A benchmark should be engraved on the top of a coping of a wing wall, etc., of each important bridge, etc., i.e. at a place where it is not likely to be injured or displaced. Where such works are far apart, special benchmark stones should be erected on good concrete foundations to avoid settlement, and at intermediate intervals.

(viii) An engraved date stone should be placed on a central part of an important bridge to give the year of its construction. The stone should not project from the face of the work, but should be slightly recessed in it.

(ix) Where a cross-drainage work (such as a level crossing —Art. 306 (*a*)) has no parapet, a header stone should be fixed near each end of it on the left-hand side as seen when approaching it, and on this its number can be engraved. The stones may be similar to furlong stones (Art. 308 (*b*)) in size and position, and should be fixed above high-flood level.

(x) Timber-topped bridges should be avoided as far as possible, for, being of a temporary nature, they require frequent renewal. Iron-topped bridges are liable to rust, especially in coast districts; probably there all ironwork should be cased in concrete or reinforced concrete substituted for it. Masonry arches look best, and are most permanent; they should be built wherever it is economically possible to construct them. In new works the arch-rings should be set to project, say, ¾ inch from the face, and the keystone another ¾ inch.

(xi) Each officer should maintain a register of all cross-drainage, etc., works in his charge. This should give the description of the works, their consecutive numbers, their mileage, the numbers and spans of their arches, etc., the height of springing above bed, the rise and thickness of arches, etc., the thickness of the piers, and a description of the abutments, wings, etc.

305. Bridges, Culverts, and Slab Drains.

(*a*) *General.*—The location of such works on a road is frequently limited by the desire to preserve the general alignment as straight as possible. For important works this consideration in the interest of traffic has to give way to the necessity for securing good sites for them; for less important ones small deviations from the general alignment are permissible. as such will not much increase the length of the road.

When an old road has to be crossed by a new railway or canal passing under it, the bridge required to carry the altered road should preferably be on the old alignment, so as not to introduce new and reversed curves. During the construction of the bridge the roadway will then have to be diverted temporarily.

The remarks made about the following particulars in respect of canals apply generally to roads when relevant to them:

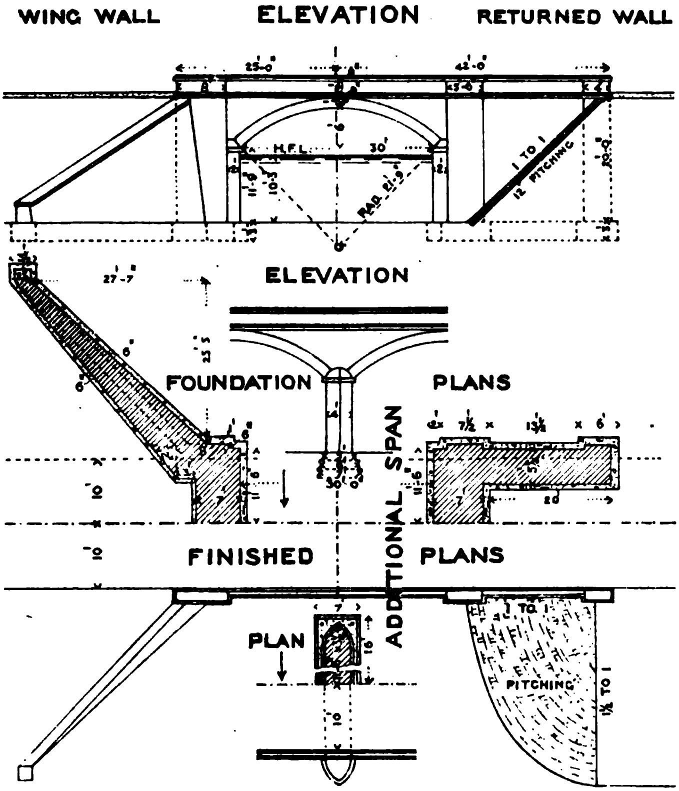
Foundations	Article 37
Retaining Walls	Article 38
Wing Walls	Article 39
Details of Masonry Cross-Drainage Works	Article 152

In regard to the table in (*f*) of the last-mentioned Article, for roads the rise of arch may be made one-fifth of the span and the thickness of the arch ring uniform throughout, and a little less than that therein given for the crown.

(*b*) *Bridges.*—Bridges for district roads may be timber-topped, iron-topped, or may have masonry arches; the last-named being most permanent, are dealt with here. The other forms have as advantages the greater waterway they offer for the passage of abnormal floods, drift timber, etc. and the less blocking of the waterway by the narrower width of the piers; iron-topped ones can also be constructed of longer spans, and thus with fewer piers than is usual in the case of arched structures. The arches of bridges are generally built of stone or brickwork, but reinforced concrete has recently

FIG. 181

BRIDGE

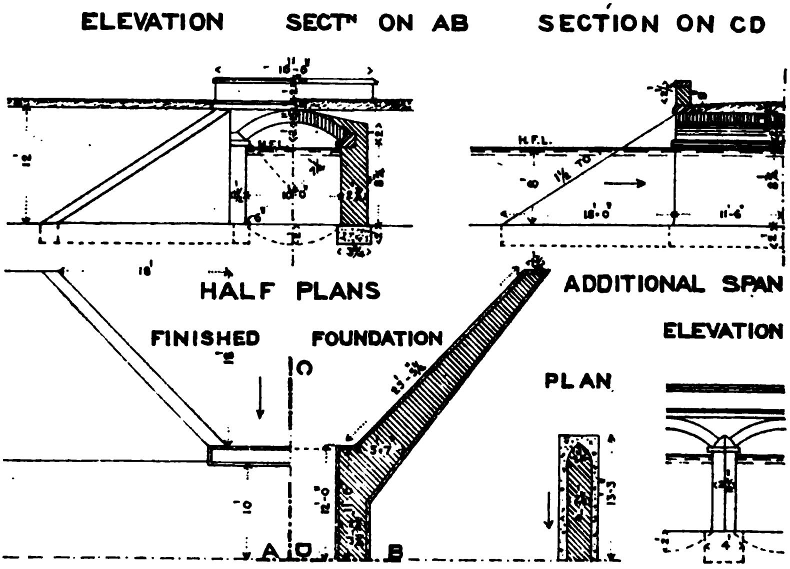


been adopted for them. The junction with the road embankment may be effected either by splayed wings or returned walls (Fig. 181) ; the former protect the toes of the approach embankments from the rush of flood water ; the latter do not do this by themselves, and the required protection is therefore given by pitching the banks at them, but their parapet walls afford greater safety to the traffic, which is useful when the embankments are high. The returned walls act as counterforts supporting the abutments, and may reduce the amount of reconstruction necessary should a moderate increase of flood waterway be required in the future. Wing walls are the best form when the stream crossed has a high-flood velocity, and returned walls when it has a low one.

(*c*) *Culverts.*—The remarks made in Article 155 apply, except that staunching rings are not necessary for road culverts.

FIG. 182

CULVERT

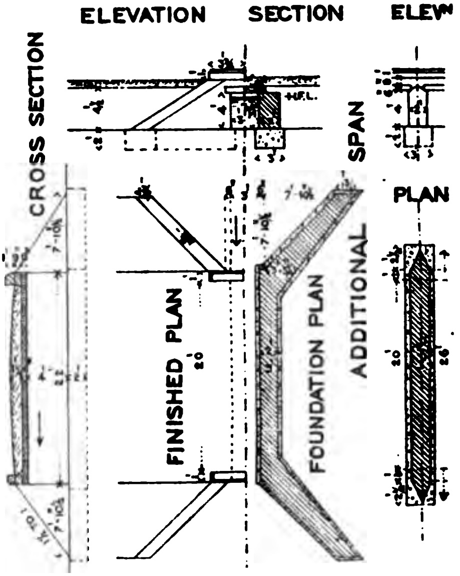


These works are suitable for crossing small streams which have defined and moderately high banks (Fig. 182).

(*d*) *Slab Drains.*—The remarks made in Article 156 apply. The alternative on roads to a slab drain is a dip. The former is the superior of the two, as it carries the road above high-flood level, and will reduce by more than high-flood depth the amount of ascent to be negotiated by traffic (Fig. 183).

FIG. 183

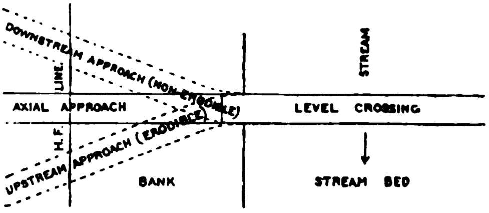
SLAB DRAIN



306. Stream Crossings.

(*a*) *Level Crossings or Dips.*—These form the cheapest kind of stream crossing, and are of a primitive nature suitable only to third-class roads, or to more important roads when they have to pass across streams with wide beds and short-lived flow, which it would be expensive to bridge. The roadway is led down each bank at a gradient, which usually should not exceed 1 in 20, and across the stream with a level, unbarrelled surface, and, if possible, at right angles to its flow and on its bed. The crossing thus resembles that shown in Fig. 185 without its side walls. The toes of the approaches of deep streams with high banks, if in soft soil, should be aligned to curve slightly downstream (Fig. 184) in order to let floods glide past them; or, if axial, they should be set well back from the line of current. If they projected axially into the stream, and still more if they pointed upstream, they would offer an obstruction to its flow, and would be liable to

FIG. 184 DIP APPROACH


DOWNSTREAM APPROACH (NON-ERODIBLE)
STREAM
H.F. LINE
AXIAL APPROACH
LEVEL CROSSING
UPSTREAM APPROACH (ERODIBLE)
BANK
STREAM BED

erosion. If, however, the natural bank is hard, the alignment may be at right angles to the stream, unless this greatly increases the amount of cutting in the approaches.

Should the stream bed be regular and the flow gentle, the crossing may be metalled; should the flow be rapid, it may be paved; and also should the bed be irregular, scour channels may be blocked by short curtain walls and the roadway paved upstream of them, while rock outcrops may be levelled. If the stream has a small long-lived flow, that might be passed through a small slab drain built at the deepest scour channel so as to secure a dry road for most of the year. The approaches will probably require repair after the close of the rainy season, when they should be re-surfaced to proper section with hard material, consolidated by watering and ramming. A thick sand coating, natural or applied, should not be allowed, as it effectually retards carts endeavouring to gain pace out of the stream for the ascent in front of them. If the crossing is in deep soft soil, the bed and the approaches up to 2 or 3 feet above high-flood level should be excavated at least 2 feet deep, and made up with sound hard material consolidated. The drainage above the approaches should be diverted from the roadway, and that from the approaches themselves confined in paved side gutters.

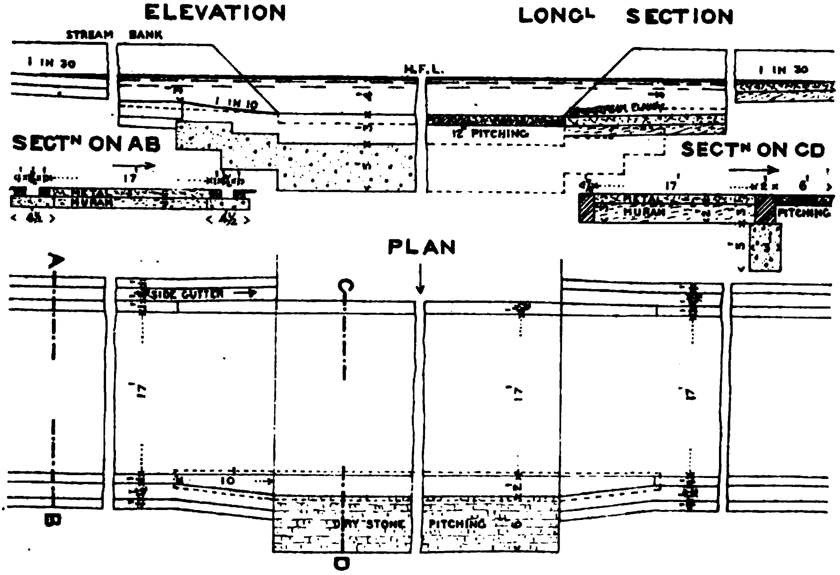
(*b*) *Road Dams.*—These are sometimes called "Irish bridges"; a type drawing for them is sketched in Fig. 185. They consist of two parallel curtain walls, of which the downstream one should be securely founded, and between these the roadway is formed. The curtain walls should be extended as returned walls or flanks, for, say, 10 feet on each side, so as to prevent the work being outflanked. These flanks should rise slightly so as to contain small floods, and the gradients of the roadway behind them might with advantage be steepened to, say, 1 in 15, so as to get quickly above the limit of prolonged submergence. If the stream crosses the roadway obliquely, the level part of the crossing should extend from where the natural bank on one side meets the current upstream at the acute angle to where the natural bank on the other side similarly leaves this downstream, so that the ascents from it may be regular, and their bases may not project into the stream. If the flow of the stream is gentle and the bed fairly hard, the road dam may be of some little height, say, 5 feet; if the conditions are the reverse, it should not exceed

3 feet. When practicable, a small slab drain should be formed through the road dam to pass off fair-weather flow, and thus then secure a dry roadway.

Another type of road dam consists of a rubble mound carried across the stream. It should have a top-width at least 4 feet wider than the roadway, an upstream side slope of from 1 to 2 to 1, and a downstream one from 2 to 4 to 1, according as the stream is slow or fast, and the latter should be carried down well below the limit of scour. The top should be paved, and the surfaces of the slopes formed with large-sized pitching or boulders laid header-wise to them (see Fig. 52, p. 254). In course of time it is probable that the mound will silt to a fairly water-tight mass, and also that the river bed upstream will silt up.

FIG. 185

ROAD DAM



All road dams should have guardstones 1¼ feet high fixed on both sides at clear intervals of from 3 to 5 feet to direct traffic between their lines.

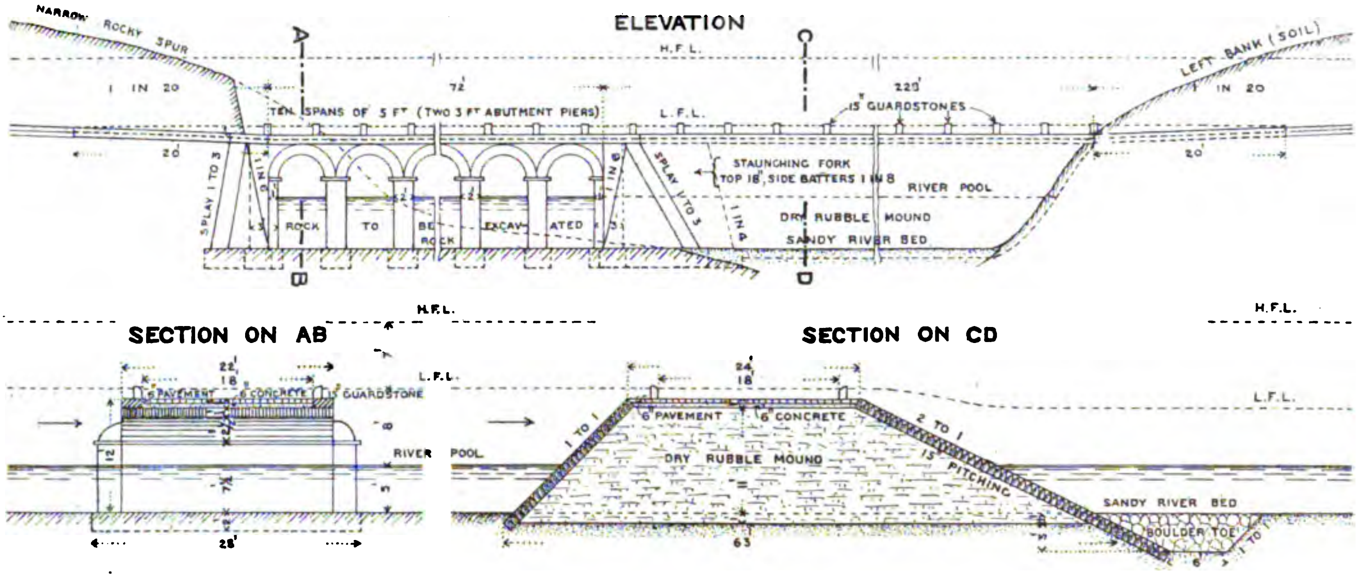
A road dam is superior to a level crossing, as it diminishes the height of ascent for traffic. The former should be substituted for the latter when the stream bed is rocky and irregular in cross-section.

(*c*) *Submergible Bridges.*—The idea of letting small fair-weather flow pass under a road dam through a slab drain has been developed by designs for a submergible bridge or causeway, or a combination of the two (Fig. 186). Instead of the bridge being constructed to discharge the high-flood entirely under it, it is built to pass only a small flood, while greater floods flow over it, and the structure is designed to withstand their action on it, e.g. solid parapets are replaced by stout horizontal bars of wrought iron piping, or old rails, carried by masonry standards raised on the piers. This form effects very great economy in districts, such as the sea littoral below the Western Ghâts of the Bombay Presidency, which are traversed by numerous large torrents that have heavy floods at intervals during the rainy season, and a moderate flow between these, but are practically dry during the fair weather. The inconvenience of the road becoming impassable during large floods is but slight, as the traffic is, anyhow, suspended owing to the intense rainfall which produces them. On the other hand, the great benefit of bridged crossings is secured for most of the rainy season, and during the whole of the fair season. If there is not a natural pool below the site of such a bridge, it is desirable, if practicable, to make an artificial one, or water cushion, by constructing there a raised bar across the stream, so as to protect the toe of the rubble mound causeway.

(*d*) *Ferry Crossings.*—Large and deep unbridged rivers with long-continued flow can be crossed by means of wire ferries. The cable, or wire rope, is supported at each bank by a standard of, say, 12-inch × 12-inch timber, strutted if necessary, and embedded in a masonry plinth, which may, if required, be raised as a truncated pyramid. On the rope runs a cradle, which should have two wheel runners fore and aft, as thus it will travel more smoothly than if it had only one. To the cradle are attached two cross-cables, the other ends of which are fixed fore and aft to the ferry boat to enable it to be set at an angle to the river whereby the force of the current impels it across to the opposite side ; the return journey is made by reversing the angle of the boat. The main cable is anchored on the river bank usually by twisting it round several anchoring posts ; such posts, however, are not likely to take the strain equally, and when one is drawn by the

FIG. 186

SUBMERCIBLE BRIDGE AND CAUSEWAY



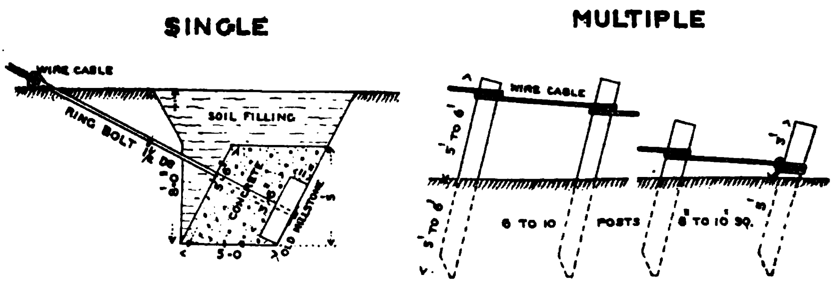
ELEVATION

SECTION ON AB

SECTION ON CD

tension the others may follow. It is better to have a single secure anchorage to avoid this, as shown in Fig. 187. The wire cable can be tightened by a tightening bolt easier than by a crab winch.

FIG. 187 FERRY ANCHORAGES

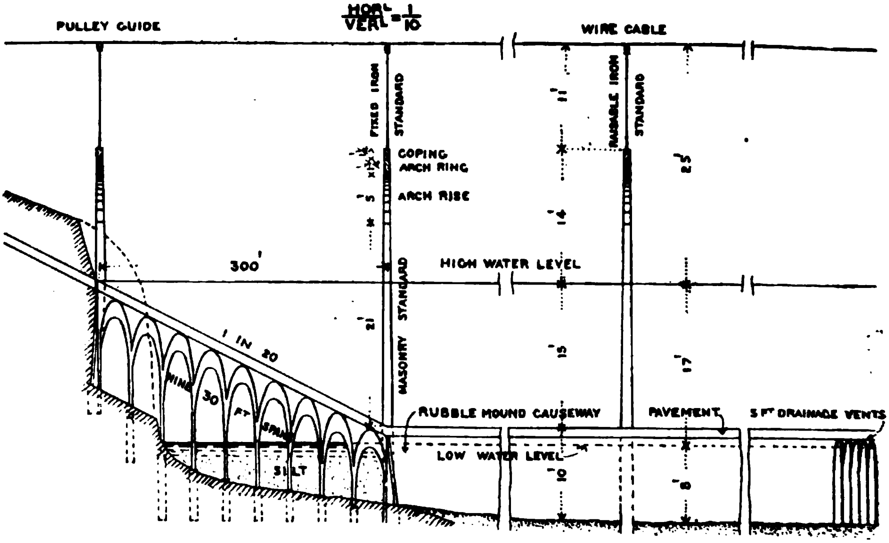

SINGLE

MULTIPLE

A more elaborate design (Fig. 188) was proposed for the crossing of a large estuary, navigable above low tide, by the traffic to and from a small town, which was not, however, of sufficient importance to justify a steam ferry. This consisted

FIG. 188

FERRY APPROACH AND CAUSEWAY



of a rubble mound causeway pierced with discharge vents, which on ordinary occasions could be traversed by carts at low tide, and on each bank was an inclined causeway approach carried on arches, rising from low-tide level up to the surface roadway above high-flood level. As alternative approaches, the ends of the causeway could be sloped up towards the natural banks or continued level to them, and the inclines therefrom excavated as cuttings in those banks, but these designs would not be so good for the working of the ferry. A wire cable was to be carried across the estuary and was to be supported by masonry standards at intervals, so as to enable a ferry boat to be worked across at higher stages of the tide. The road traffic was to be suspended at intervals then, and the central iron standards, and thus the central part of the cable, raised to allow country craft to proceed up and down the estuary.

(*e*) *Flood Limit for Crossing.*—As non-local traffic using roads which have any of these forms of stream crossing may not know when it is safe to traverse them during their submergence by floods, indicators and danger notice boards should be fixed to give this information. The indicators may be dressed stones conspicuously fixed on each bank with the safe flood limit engraved on them, or figured vertical standards of 4-inch diameter wrought-iron pipes painted in foot-wide bands, say, alternately black and white below, and red and white above that limit. Even with ferries this precaution is necessary to prevent them from being worked when the height of the flood would make this dangerous.

307. Ghát Roads and Retaining Walls.

(*a*) *Ghát Roads.*—A ghát road is the name given in India to a steep and long hill incline. In the Bombay Presidency there are several rising continuously for some 5 miles for a total ascent of some 2,000 feet; in the Himalayas there are still longer inclines up greater ascents. They wind in and out between sharp projecting spurs, generally in cutting with the steep hill slope on one side, and a considerable precipitous descent on the other, and they are traversed by numerous hill torrents, most of them small, but with very high velocity. The general alignment is very tortuous; in one well-known ghát the road in a descent of 10 miles is never 5 miles distant from its start.

In Chapter XXIV the following particulars have been mentioned in respect to ghât roads:

Alignment—Article 286 (end of);
Curves (also " hair pin " curves)—Article 288 (beginning and middle of);
Cuttings, drainage of slopes—Article 290 (*b*);
Surface drainage—Article 292 (*c*);
Camber—Article 299 (middle of (*a*)).

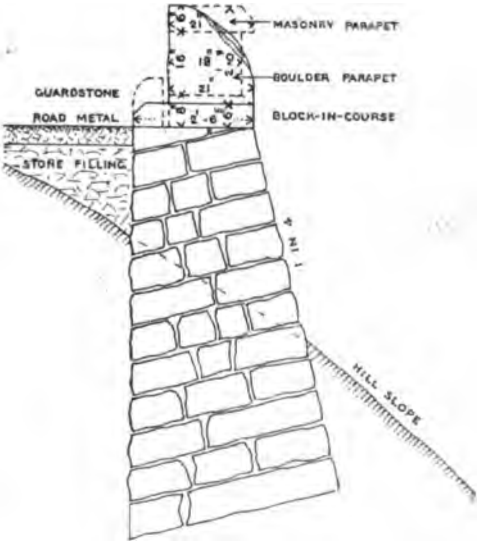
Wherever practicable, the alignment should be led across broad spurs, where the gradient may be flattened; the ruling gradient should, if possible, not exceed 1 in 15; and descents which have to be made good by increased ascents further on should be avoided. Where the line of traffic on a curve is not parallel to the centre line of the road, but makes a greater curvature, it shows that the original road curve should be flattened. Landslips may take place at deep cuttings, despite all drainage precautions; the fallen *débris* should be removed at once. A larger precautionary measure consists in the afforestation of the hill slope so as to reduce the rate of run-off. The ordinary camber falling on each side from the centre line of the road should be replaced by a gentle uniform slope downwards from the precipice side to the hill side. This, of course, diverts all the road drainage to the latter, but the total catchment areas of its road gutter are thus not doubled, while those of cross-drainages are thereby proportionately increased only by very small amounts. It is much more important to protect the ground on the precipice side from the scouring action of spill water from the road. The road metal used should be small, so that it may be consolidated more easily and may form a smoother surface. It will probably be difficult to arrange to stack heaps of it at regular intervals, as nowhere must the heaps encroach on the roadway. They should be placed on levelled platforms out of the way of traffic, and thus in shape may have to be long and narrow.

Small culverts and slab drains for cross-drainages with a very steep fall are constructed in a corresponding series of steps in longitudinal section. Large culverts and bridges, however, have their springing line level, as the streams they are on usually have comparatively gentle inclinations.

(*b*) *Side Protection.*—Throughout the whole length of the ghât traffic must be prevented from falling down the precipice side, and must particularly be guarded at curves. The best form of protection is a boulder parapet (Fig. 189), but this is unfortunately the most expensive type. The boulders are set on a course of block-in-course masonry laid in lime mortar, which is carried by rubble masonry walling securely founded. The boulders should be as wide as possible to increase their weight and resistance to disturbance by impact (12 to 24 inches face in trap and 18 to 30 inches in laterite); they should be only roughly dressed, and should be laid in lime mortar. Rubble parapet walls are cheaper; they should be about 2½ feet high and 1½ feet wide, should be properly founded, and well built with good face stones, and headers at intervals of from 5 to 10 feet in each course; the hearting should be of large-sized stones, with only vertical chips wedged in, and there should not be small stones nor chips on the face. Where the precipice side is not steep, banks 2 feet high and 2 feet wide at the top can be formed along the roadside, but so that their inner toes do not encroach on the roadway; strong hedges should be planted on them, and not be allowed to grow more than 3½ feet high.

FIG. 189

GHÁT RETAINING WALL



(*c*) *Ghát Retaining Walls.*—The ordinary cross-section of a ghát road consists of excavation on the hill side and embankment made of the spoil on the precipice side. Where, however, the hill slope is very steep a simple embankment cannot be formed, and a retaining wall has to take the place of its downstream portion, and may be of considerable height (Fig. 189). The retaining wall must be securely founded, so that it will not slip down the hill side. Its outer batter should be 1 in

4, and its back should be vertical, plane for low walls and broken into off-setted steps for high ones. The foundation course should be normal to the outer batter, and should consist of long and flat headers, laid as close as possible to each other, and thereafter wedged tight by vertical spauls driven into the interstices; rough headers not less than 3 feet long and 6 inches thick should be inserted at 10-feet intervals in this course, and breaking joint with each other in each course throughout the wall. The upper courses should similarly be laid normal to the outer batter, so as to give the wall active resistance to the earth pressure. The face stones should be built alternately as headers and stretchers, and should not be less than 1½ feet long for the top 6 feet of the wall and 2 feet long for the rest of it, and they also should be wedged tight by vertical spauls. Where the single main headers do not extend throughout the wall, two or more should be laid in line across the course. All vertical joints should break joint; all stones should be laid flat, and none should project beyond the face. During construction the wall should be kept 3 feet above the backing, and that should consist of rock *débris*, or of shaly or gritty, clayey soil laid in 6-inch layers normal to the outer batter and well rammed. The top of the retaining wall should be finished off with a parapet wall, either of ordinary masonry, or formed with boulders.

308. Milestones and Furlong Stones.

It is desirable, in the interest both of travellers and of the staff in charge, that roads should have proper mileage stones fixed.

(*a*) *Milestones.*—A milestone should be visible from some distance off, and, where practicable, the view of it should be unobstructed. To secure such visibility it is best to have it oil-painted white, so that it may stand out from its background. The words and figures on it have to be read from a short distance only, and may be black; these on a white ground will be quite distinct and easily read. If the stone were coloured black and the figures, etc., white, the former would not be visible at a distance. The words and figures should preferably not simply be painted, but should also be cut (V-shaped, in order that the arices may be preserved unbroken) so as to be permanent, less likely to be obliterated by dust, and easier cleaned when thus hidden; engraved stones should be fine grained, so that the engraving may be sharply cut. All roadside stones should have their centre of gravity well below the ground surface, so as to increase their stability, and therefore the part embedded should be of larger section than that above ground; they should be set truly vertical. Distance stones should be fixed on the left-hand side of the road in the direction of the mileage. They should be placed, say, 10 feet away from the edge of the road, so as not to get covered with dust, and yet so as to be easily legible.

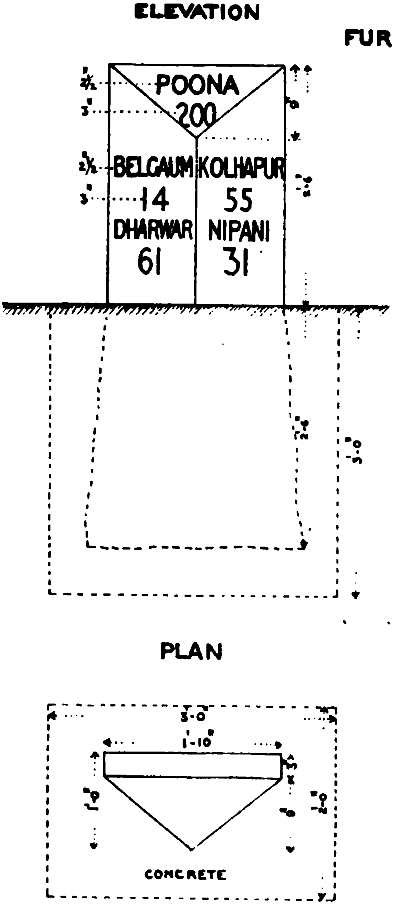
Fig. 190 shows a good pattern for a milestone; its form can be reproduced in cast iron, which will last a long time if kept painted. The front faces and top should be dressed fine; the back and underground parts should be left rough. On the top sloping face should be the name and mileage of the town at which the road ends, and on the two vertical sides the names of the nearest large and principal towns of the district facing the direction in which they are being approached.

On an existing road which is being improved in alignment the milestones should not be shifted until all the alterations behind them have been effected, for new diversions will alter the mileage subsequent to them. As milestones are thus liable to be changed, it is not advisable to utilise them as permanent benchmarks; those can better be fixed on cross-drainage works, especially if these are numerous, or on special stones securely founded where such works are far apart.

(*b*) *Furlong Stones.*—The dressing, engraving, bedding, and distance from the road of these should be similar to those described for milestones, but furlong stones (Fig. 191) should be much smaller. To distinguish them at a distance from boundary stones (Art. 309) they may have their tops dressed half-round, and they may be coloured differently. They should be engraved with the number of the miles as numerator in figures, say, 2½ inches high, and the number of the furlong as denominator in figures, say, 2 inches high. It is unnecessary, and undesirable from the point of view of legibility, to add " M " and " F " before the figures which indicate the number of the mile and furlong respectively. They should not be treated as boundary stones, nor is it necessary to place them on each side of the road, nor at the ends of miles behind the milestones.

ROAD MARKS

FIG. 190 MILESTONE


ELEVATION

PLAN

FIG. 191 FURLONG STONE

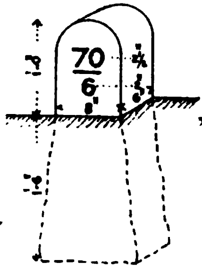


FIG. 192 BOUNDARY STONE

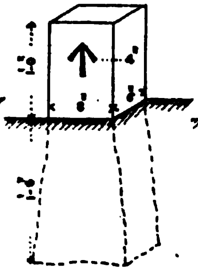


FIG. 193 GUARDSTONE

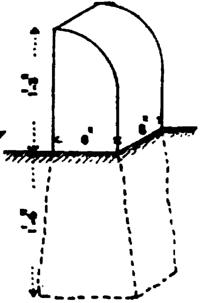


FIG. 194 SIGN POST

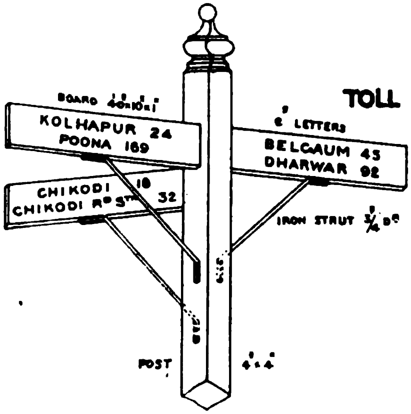


FIG. 195 TOLL NOTICE BOARD

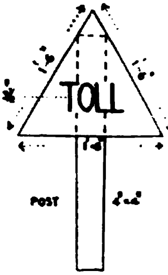
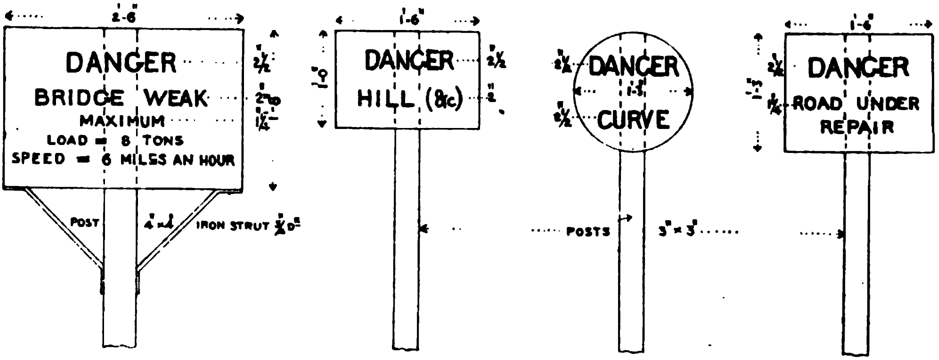


FIG. 196 DANGER NOTICE BOARDS



The positions of all works in a furlong should be described as being in the furlong marked by the preceding stone.

Half-furlong stones are not required as distance marks, but will be useful to define half-furlong material stacks (Art. 301 (*c*)), for which purpose only the half-furlong may be marked thus—$5\frac{1}{2}$—without the mileage.

309. Boundary Stones and Demarcation.

Boundary stones need have only their face next the road roughly dressed; it will suffice if their tops and other exposed sides are roughly squared. They should be whitewashed, and on them should be a distinctive mark indicating the proprietorship of the road (e.g. a broad arrow if the road is a Government one); this should be engraved and painted black on the side facing the road (Fig. 192). The letters "R.B.," indicating "road boundary," are unnecessary and expensive to engrave.

All land acquired for roads, quarries, buildings, etc., should be demarcated by boundary stones soon after its acquisition. The boundary line of roadside property (Art. 291 (*c*)) should be set out to give full space for all requirements, and the stones should be fixed on it. The spacing of the stones along that line should be regulated by the nature of the alignment and of the land traversed, i.e. it should be closer on curves than on straight lengths, and also where encroachments are likely to take place (near towns) than where these are not probable (on barren hill spurs). Where the roads pass through areas locally administered (by municipalities, etc.) their limits should be carefully and distinctively marked. The positions of boundary stones should be verified from time to time, especially where encroachments are probable, and such should be dealt with at once before they become practically permanent and cannot readily be removed. To enable this inspection to be done a register should be maintained; this should give the road mileage, and the side widths of the property measured from the centre line of the road at all points where the alignment of the boundary changes, and elsewhere as may be necessary.

310. Guardstones and Protective Works.

(*a*) *Guardstones.*—Guardstones should be from 15 to 18 inches above ground, and of about the same depth below it.

The above-ground portion should be about 8×8 inches in section and roughly hammer-dressed; the below-ground portion should be undressed and as large in section as practicable, in order to secure stability. On bridges and causeways the stones should be fine dressed, and have their tops cut to a quarter-round, facing the road or the direction of stream flow respectively (Fig. 193). On the latter works they should not project more than 18 inches above the pavement, so that they may not be washed away; the stones should be fixed 3 inches clear inside bridge, etc., parapets. Guardstones should be spaced from 3 to 8 feet clear on the precipice side of ghâts, in front of retaining walls, and on road banks more than 5 feet high; the more dangerous the place, the closer should be the spacing. They should be fixed to regular lines and curves, and as far from the edge of the metalled road surface as practicable.

(*b*) *Protective Works.*—Guardstones should be looked upon only as indications of danger; traffic should be protected from such danger by more substantial barriers, such as parapet walls, banks, or hedges in addition (Art. 307 (*b*)).

Hedges should be of strong and stout plants which will easily grow locally, and in good continuous lines without gaps. They should be planted at the proper season where practicable on the precipice side of ghâts and along high banks and approaches to cross-drainage works, right up to their parapets. They should be set out about 3 feet from the edge of the road, so that they may not interfere with traffic, and also so that they may not be too low down the embankment to prevent runaway carts, etc., from falling down its slope. Similarly, to give additional protection as well as shade, trees might be planted up the slopes of high banks. Hedges should be trimmed to not more than 6 feet in height to prevent them from becoming weak and straggly; their face next the road should be trimmed well back from it.

Post and rail fences may be constructed for a short distance next to cross-drainage works; elsewhere they are in the tropics too expensive to erect and maintain, as owing to climatic conditions their life is short, unless they are kept well painted.

311. Notice Boards.

(*a*) *General Remarks.*—There are many kinds of notice boards in favour, and some patterns are shown in Figs. 194–196.

The general principles which should be followed in respect to them are:

- (i) A large number of signs is confusing; the different shapes adopted should therefore be few.
- (ii) The quicker the traffic, the greater the necessity for signs.
- (iii) Each kind of sign should have a distinctive shape, so that it may be recognised from some distance.
- (iv) Danger signs should be set sufficiently back from the point or place of danger, so as to give timely notice to traffic.
- v) The view of signs should be as unobstructed as possible, for which purpose trees, bushes, etc., in front of them should be removed, and as far as practicable the signs should be erected on straight lengths of the road.
- (vi) Notice boards should be placed at right angles to the road, so as to be more easily legible.
- (vii) Notice boards should be solid; skeleton ones are not distinct at a distance.
- (viii) The sign and its post should be of the same colour, so that the mark may stand out well against its background.
- (ix) The lettering on signs should be bold and concise, so that it may be easily legible; for this purpose it should be in plain vertical block, with all lines of equal thickness.
- (x) Notice boards as a rule should be erected on the left-hand side of the road from the direction of approach to them.

The bottoms of all notice posts should be well tarred, and should be set at least 18 inches deep in concrete, which should have its top rounded off just above ground level, so as to shed the rainfall. The bottoms of all notice boards should be about 7 feet above general formation level. All should be kept well painted, and, in particular, the lettering should be maintained clear and distinct, for which purpose it is best to have its letters cut in the boards, or to substitute enamelled plates for the boards.

(*b*) *Direction or Sign Posts* (Fig. 194).—These should be fixed at all made cross-roads. There should be one arm pointing down each road, and on it should be neatly cut and painted in black the name of the nearest or principal town and its mileage distance. The boards should be plain-ended, and need not have finger hands painted or cut on them. The posts and boards may be painted white, and they should always be kept in thorough repair. When necessary, the arms may be lettered on both sides; when not in line with each other, they should be placed at different levels, so as not to obstruct the view of each other; the lowest board should have its bottom about 7 feet above the road surface. When only one road branches off, the sign should be placed on the side opposite to it.

(*c*) *Toll Notice Boards*[1] (Fig. 195)—These should be fixed 100 yards on each side of the toll bar. The board may be a solid equilateral triangle of 18-inch sides, with its base horizontal, and about 6½ feet from the ground, and its plane at right angles to the road. On it should be painted TOLL in white block letters 3½ inches high; the lines of the letters should be ½ inch thick, and the bottom of the word 3 inches above the base of the triangle. Both the board and the post should be painted vermilion.

(*d*) *Danger Notice Boards* (Fig. 196).—These should be fixed some distance on each side of the point or length which is dangerous. The board and post of the "Hill" sign (also for "ghâts," "steep gradients," "bridges," "crossings," "high bank," etc.) may be painted white, and those of the other signs red; the lettering may be in black for all.

312. Roadside Avenues.

(*a*) *General Remarks.*—While a canal avenue should consist of fruit or revenue-producing trees, a roadside avenue in the tropics should be formed of shade-giving ones, which will not only afford comfort to travellers, but will tend to prevent the road surface from drying up and becoming friable and dusty in the fair weather. The remarks made about the former (Art. 47) apply generally to the latter. Additional ones which have reference to roadside plantation work are noted below.

(*b*) *Spacing of Trees.*—To prevent interference with traffic, trees should not be planted nearer than, say, 12 feet from the edge of the roadway; nor on the inside of sharp bends, so as to obstruct the view along the road; nor in the way of telegraph lines, etc. Where the rainfall is great and the rainy season prolonged, trees should be set back, so that the dripping from their branches does not roughen the road surface. There overhead shading is less necessary on account of the more exuberant vegetation and the road requiring drying by exposure to the sun and wind.

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[1] The modern policy in India is to abolish tolls, and thus free from charge road transport, which benefits the whole community.

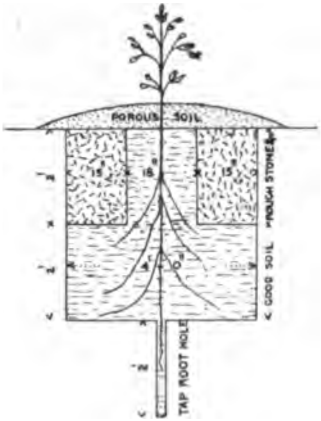
(*c*) *Nurseries, Seedlings, and Cuttings.*—Water is a difficulty on some roads, and nurseries there have perforce to be started where only it is available. Generally, however, there will be a well or other source of supply near establishment quarters, which will then be the best location so as in addition to secure supervision and protection. Nurseries should otherwise not be on the roadside, as they are there liable to be injured by cattle, etc. On account of the water difficulty seedlings should be well established in the nurseries before they are planted out finally.

Cuttings can be successfully made in India from most trees of the fig tribe, which give excellent shade as they arch over the road. On account of their widespreading roots they should not, however, be planted near masonry works. They should be cut from straight branches from 8 to 10 feet long, and their natural lower ends should be buried from 2 to 3 feet deep in the ground. They should be planted out as soon as they are cut, and after the first downpour of the rainy season. They should be watered up to the commencement of the next rainy season, and not afterwards. Before the cutting is planted, all small branches should be lopped off, and the cut ends and top of the cutting should thereafter be covered with mud and cowdung mixed to prevent them from drying. Some consider it advisable to injure the bark of the embedded end slightly at one or two places so as to induce roots being thrown out there. In order to lessen the risk of failure, and thereby the formation of gaps in the avenue which will have to be replanted, two cuttings may be set in each tree hole; the inferior one should be removed at the beginning of the next rainy season. With stout well-bedded cuttings fences are unnecessary—sufficient protection can be given by tying thorns to the stems.

(*d*) *Planting Out.*—As watering is very expensive on the roadside, every precaution should be taken to secure the rapid growth of seedlings with the fewest number of waterings.

Good tree holes, 4 feet cube, should be dug well in advance, so that the soil may be aerated ; the excavated soil, if necessary, should be made pervious by the admixture of gritty stuff (sand, gravel, fine road metal, etc.) before it is refilled. In addition some place a porous earthenware jar in the hole, so that water may be poured into it, and thus gradually moisten the earth. The objection to this plan is that, unless the jar is moved at intervals, the tree roots are apt to grow lop-sided. A better arrangement is sketched in Fig. 197. Good earth to which old manure, if possible, has been added, or road silt, dead leaves, etc., is filled in at the bottom of the hole. On this is built up drystone of the roughest and cheapest description (quarry rubbish, sand, etc.), leaving a cylindrical space in which the seedling is planted, and is surrounded by good soil, and the top is finished off with clean porous material. When the seedling is watered, practically all the water descends evenly all round to the bottom of the drystone, very little is evaporated from the surface, and the rootlets are thus induced to grow downwards, and are thereby protected from drying by the sun. The holes cost a little, but much less than the value of the waterings they save, and they give the seedling a good start.

FIG.197 TREE HOLE



Where the ground is rocky, instead of blasting out holes, the trees may be planted on mounds of earth, raised about 2 feet high and 6 feet in diameter on the surface, which should be dug as deeply as practicable to seat them. Where the ground is hard it may be possible to get roadside material from pits dug in the line of the future avenue, which can afterwards be filled and utilised for tree plantation.

Near towns and villages the tree enclosures have to be especially good ; the cheapest efficient form is a circular ring of the roughest stone or brick and mud walling 6 feet in diameter, $3\frac{1}{2}$ feet high, and about 6 inches thick.

(*c*) *General Maintenance.*—Ordinary maintenance is required as on canals. To secure a good, uniform avenue of symmetrical well-grown shady trees the following should be attended to:

(i) The removal of trees which are inferior and damaging more valuable ones; crooked, badly injured, or irregularly grown; of kinds unsuited to the soil, etc.; out of line or irregularly spaced; of thorny varieties which are a nuisance to traffic; and of kinds which give little shade in the hot weather when it is most needed;
(ii) The maintenance of only the best stem when two or more are growing together;
(iii) The maintenance of as much shade as possible, i.e. loppings and fellings should be reduced to what only is immediately necessary;
(iv) The maintenance of trees about the removal of which there is any doubt, as this can be settled after superior inspection, but if erroneously effected, cannot be remedied.

(*f*) *Programme of Operations.*—In order that existing avenues may be completed, or new ones formed, it is desirable for each road or section thereof to make out a comprehensive estimate for all plantation work necessary, and annually to obtain allotments from the general sanctioned amount for carrying out parts of the programme. The objects which will thus be attained are:

(i) The ascertainment of the probable total cost of plantation work contemplated;
(ii) The execution of plantation work systematically and economically;
(iii) The proper control of expenditure—annual and final.

To frame and get sanction to minor estimates to cover only each year's work leads to dilatory operations, which are expensive and practically uncontrolled. To assist the control of operations it is advisable to have monthly (or in the fair season quarterly) plantation progress reports submitted, giving furlong by furlong, or mile by mile, the opening balance, trees planted, trees dead, closing balance, number of tree holes dug in advance, etc.

313. Maintenance and Repairs.

(*a*) *General Remarks.*—" Maintenance " consists in the continuous preservation of the road in a good state by means of petty works carried out by establishment permanently maintained. " Repairs " comprise the execution at periodic intervals of large works executed by gangs of labourers specially entertained. In order that maintenance should be properly performed, the roads gangmen and foremen must constantly be supervised by the sectional staff, who should see that work is tasked, and that useless jobs leading only to waste of money are not carried out, or otherwise expenditure will be frittered away.

To determine where the more extensive surface repairs should be undertaken, the engineer in charge should make himself thoroughly acquainted with the whole state of the road by annual inspections conducted well in advance of the actual operations, so that he may devise these systematically. Inspections as to other matters are also necessary. The engineer should see what special defects should be remedied in the interest of traffic, as the efficiency of a section of a road depends upon the condition of its worst part ; his principal subordinates should, as soon as possible after the close of the rainy season, inspect and report on the foundations and superstructure of all cross-drainage works.

Statistics should be kept of the costs of all operations each year in each section of the road, so as to compare the expenditure thereon in different years and on different sections of the road, or of similar sections on other roads. These costs should be taken out by units suitable for general comparison. By means of this information it will be possible to ascertain the relative wearing qualities of different descriptions of materials and under different conditions.

(*b*) *Estimates.*—Estimates should be divided into two portions—(i) Repairs, and (ii) Maintenance. To the former should be allotted from 60 to 75 per cent. of the whole, according to the nature of the road, and the balance to the latter. Each estimate should be accompanied by a survey report and a road chart showing the miles each of which received a new coat of metal in previous years. Re-metalling will probably be the largest item, and will include a provision of reserve metal for the following year, and the cost of surfacing in the current year of the metal collected in the previous year. On an ordinary part of a district road a coat of metal will probably last five years; near towns or where the traffic is heavy the surface may have to be renewed every two or three years. The average annual requirements should accordingly be provided in the estimate, so that the maintenance operations may proceed regularly and the road surface be uniformly maintained in good order.

(*c*) *Records and Returns.*—The engineer should maintain in his office—

(i) Plans and sections of the road surface and of all important works;
(ii) A statement, mile by mile, of the correct formation widths of the road—average, maximum, and minimum;
(iii) A list of all inspection and staff buildings, giving their mileage, accommodation, furniture, etc.;
(iv) Registers of all land occupied by the road, buildings, and quarries;
(v) Road charts showing the annual progress of surfacing, mile by mile;
(vi) Schedules of the rate cost of preparing materials at the quarries, and the leads and rate cost of transport per mile therefrom;
(vii) Annual inspection reports on the roads, their buildings, and the waterways of cross-drainage works;
(viii) Annual reports of abnormal floods.

(*d*) *Annual Programme of Work.*—As work has to be carried out according to the seasons, a fixed annual programme of repairs should be settled and worked to. Taking, for example, a country with the rainy season extending throughout June to October, and with fair weather for the rest of the year, a good programme would be:

(i) November to March: Early repair of flood, etc., damage; collection, stacking on roadside, and measurement of hard metal; repairing bridges and buildings; painting mileage and demarcation stones and signposts; clearing gutters, drains, and waterways; and generally putting the road into good order as soon as possible. Also the construction of new works and improvements.

(ii) April and May: Supplying balance of hard metal deficient; check measurement of hard metal; collection, stacking on roadside, and measurement of soft metal, muram, and sand for blindage; clearance of road gutters, drains, and cross-drainage waterways; distribution of rollers on roadside and tools as required for repair operations. Also the completion of new works and improvements.

(iii) June to October: Consolidation of new road surface—where of hard metal, early in the season, where of soft material, late, after checking; repairs of rain damages; gutter, etc., clearances; plantation work.

(iv) Throughout the year: Road surface patching; removing loose stones, mud, and dust; removal of landslips; petty repairs as damage occurs; plantation work.

(*e*) *Execution of Work*—(i) *Establishment.*—The gangmen should be in small parties under working gangers, who should be provided with setting out strings and pegs, metal gauges, etc., and be held responsible for maintaining their sections, and protecting traffic from danger. During the rainy season these permanent men can be employed as gangers over the large numbers of temporary workpeople. The foremen should be given comparatively long sections in the fair weather and shorter ones in the rainy season, when general surface repairs are in progress, their numbers being then supplemented by temporary foremen. They should be provided with tapes and setting out appliances, and be given instruction notebooks. They will be under the subordinates in charge of main sections, who will carry out all survey work required, frequently inspect their sections, take measurements, and prepare estimates, etc., under the control of the engineer.

(ii) *General Repairs.*—During the season when consolidation is in progress all large repairs should be executed; the labourers should be concentrated as much as possible so as to secure constant supervision; daily progress reports should then be furnished. All repair work should be done neatly, to correct lines and levels, and should be set out by pegs and strings; the edges of road banks, cuttings, and gutters should be kept level and true to section. All tree branches which come within 10 feet of the road surface, or obstruct the view along the road, should be neatly lopped ; hedges should be trimmed to section ; rank vegetation should be rooted out, anthills dug up and the queens destroyed, and, generally, the berms and bank slopes neatly maintained.

(iii) *Miscellaneous Repairs.*—Footpaths down the slopes of road embankments should not be permitted near the wings of cross-drainage works. Trees, bushes, etc., should not be allowed to grow on retaining walls, and all road drainage should be diverted from these. Pitching should be maintained to the proper slope surface, and rank vegetation should be rooted out from it. The approaches to dips should be made up at the end of the rainy season and maintained properly throughout the fair weather. Gutter clearances should be spread on the berms so as not to be washed back.

(iv) *Removal of Vegetation.*—Waterways near cross-drainage works should be kept clear of vegetation impeding their flow, and trees likely to fall into them should be removed. Trees should not be allowed to grow within 20 feet of wing walls. Large ones which have hitherto not done harm may be allowed to remain, but their roots should be cut through by a trench alongside the wing wall, and this should be filled with dry material. Vegetation growing on masonry works should be rooted out at the end of the rainy season, and the holes thus formed exposed to the sun throughout the fair season, so as to kill any rootlets that remain ; early in the rainy season the holes should be filled by mortar pointing.

(v) *Masonry Works.*—Foundations of cross-drainage works should be inspected immediately after the close of the rainy season, and all necessary repairs at once effected. Where scour is taking place, the foundations should, if required, be first underpinned, and thereafter protected by curtain walls, pitched aprons, etc. Arch rings should be inspected at the same time and repaired if defective. Pointing repairs should not be done until the subordinate has himself passed the raking out of the joints, which should, as a rule, be at least 1½ inches deep, and the deeper the better. The joints should be carefully cleaned and wetted just before they are filled, preferably with "gauged" mortar (i.e., ordinary lime mortar mixed with a little cement). The pointing should be done at the close of the rainy season, and should be kept wetted for at least ten days. The pointing mortar should just fill the spaces between the stones, should be struck with a trowel, and well rubbed with an iron tool as soon as it begins to set. " Tuck " pointing is objectionable, as it forms false joints not united to the mortar in the hearting. " Lined " joints are also objectionable as the lining separates the face of the mortar and thus weakens the joint.

(vi) *Bridge Floorings.*—Iron-topped and timber-topped bridge floors should at intervals have the road surface stripped off, should be cleaned thoroughly, and then completely painted or tarred. A record of this overhauling should be preserved, and the date of it painted inconspicuously on the work itself. The road metal coating over bridges should be maintained to its sanctioned thickness ; if too thin, the arch-rings or floorings may get injured ; if too thick, they may be over-weighted.

(vii) *Protection from Danger.*—When culverts, etc., are under repair or reconstruction, if practicable, only one-half of the work should be undertaken at one time, the other half being kept open for traffic. Should, however, the total closure of a structure be necessary, before it is carried out the road should be properly diverted for the traffic to proceed well outside the work. Whenever a portion of a road or a structure in connection with it is under repair, or is damaged, and danger to traffic may result therefrom, all proper precautions must be taken to avoid accidents. Barriers should be constructed across the road on each side, or round the area of the structural repair, and at night time lights and watchmen provided. Danger notice boards should be fixed some distance off on each side, and lights exhibited thereat at night time. The repairs should be executed as rapidly as possible. Dangerous parts of the road should be securely protected by hedges, parapets, etc., and danger notices fixed. Metal and materials should nowhere be stacked, nor rollers left unguarded, within 8 feet of the edge of the road surface. Parapet walls should have their ends whitewashed so as to indicate them at night time.

(viii) *Repair Estimates.*—The necessity for non-emergent or extensive repairs should be reported with approximate statements of their probable cost. Detailed estimates for them should not be submitted until these are called for, so as to avoid loss of labour should funds for execution not be forthcoming. Urgent special repairs should at once be reported, with proposals and rough estimates of cost. Orders as to putting the work in hand should be awaited, except in cases of great urgency, when construction should immediately be commenced in anticipation of formal sanction and the fact reported. All work included in or provided for in a sanctioned estimate for which an allotment has been granted can be undertaken without further orders, unless these are specially communicated.

314. Improvements.

As the requirements of traffic increase on an old road, improvements to it may become necessary; in other cases the original condition may necessitate betterment. On his inspections the engineer should make notes of all that is wanted in this respect, and the relative order in which the works should be carried out, so that dangerous portions, or those which are especially obstructive to traffic, may receive prior attention. Improvements may be classified as—

Major, requiring special estimates for their execution;
Minor, which can be executed out of the current repair grant, for which purpose, say, 5 per cent. of the total allotment should be reserved.

The following list gives an indication of improvements which may be desirable:

Major Improvements.

Improving alignment by large diversions;
Reducing steep gradients;
Widening roadway;
Improving class of surface;
Increasing depth of metalling;
Forming side widths where non-existent;
Constructing new cross-drainage works;
Improvements of cross-drainage works (e.g. replacing a dip by a slab drain);
Strengthening bridges.

Minor Improvements.

Petty straightenings;
Easing curves;
Equalising "switch backs" (ups and downs);
Cutting down crests of saddles;

Improving gradients of approaches to dips;
Dressing off tops of cuttings (to prevent landslips);
Improving road crossings;
Removing obstructions to view;
Extending kerbing;
Extending flanks of road dams;
Extending protective works;
Providing or extending catchwater drains;
Improving waterways of cross-drainage works;
Making dangerous places safe.

If a road is generally in fair condition, the annual construction of small improvements will put it into a good state in a few years. If, however, a road requires much to be done to it, it is advisable to embody all of its improvements in a special estimate, and carry them out in one or two seasons. In any case, the resultant benefit to traffic will be out of proportion large to the cost involved, seeing that the bulk of the expenditure has already been incurred on the construction of the road.

315. Road Administration.

In England and Wales there are said to be 1,850 local authorities interested in the management of roads, and a case has been cited in which six public bodies are responsible for separate portions of a length of 1½ miles. The result is that there is much diversity of practice and of the standard of maintenance. There the general opinion of engineers[1] is much in favour of centralised control which might be exercised by County Councils for all ordinary roads in the areas administered by them, and by Government for lines of through traffic, as these pass through several locally administered areas, and as the traffic is of a general, not local, nature. Until such control is established it is impossible to expect that the same high standard will be preserved on all roads, and that their general improvement will be effected. In many other countries roads are placed under a Government department, and notably in India, where there are old military roads, some of which are over 1,000 miles long. The advent of motor traffic, which demands a uniform and high standard of upkeep over considerable distances, points to the necessity for central control, even if areas are locally administered. If such areas are large and important enough to enable a superior engineering staff to be maintained, the local authority could safely be entrusted with the administration of the roads therein. With small and unimportant areas such a staff could not be entertained, and centralised administration becomes desirable, the local bodies being consulted as to financial arrangements. The advantages of centralised management are that it:

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[1] Minutes of Proceedings, Inst.C.E., Vol. CLXV; "A Plea for Better Country Roads," by G. R. Jebb, M.Inst.C.E.

- Enables a properly qualified engineering staff to be maintained;
- Allows construction and maintenance to be better carried out, and to fixed standards;
- Effects economy in engineering, labour, and materials;
- Permits better plant to be employed;
- Prevents diversity of systems and maintenance on parts of the same line of communication;
- Assists in developing improved methods of construction and maintenance;
- Facilitates experimental and statistical work which lead to improvements;
- Obviates the delay and possible friction entailed by endeavours to obtain the co-operation of numerous separate authorities;
- Results, for all these reasons, in improving traffic facilities.

316. "Tar-bound" Roads.

The remarks made previously on the surface of the road (Art. 294) had reference to "water-bound" roads, which on account of their cheapness will probably always be the ones adopted for district roads in the tropics and in rural areas generally, as these cannot stand the expense of tar-binding. Where, however, such roads pass through or near urban areas, it may be considered desirable to improve the surface and to make such sections "tar-bound"; there better scavenging is necessary, and greater facilities for tarring exist. It is not likely that expensive wood or asphalt pavements will be laid, and wood especially might not withstand the climate and general conditions of a hot country.

Natural asphalt is a limestone rock impregnated with bitumen in certain proportions. It is made into powder, heated, laid on the road, and welded together by being beaten with heated rammers. It is more permanent under weather conditions than artificial compounds, as it does not volatilise so readily as they do, but under the long continued and intense heat of a tropical sun does thus disintegrate eventually. It softens under heat, and then becomes plastic and liable to be worn by iron tires into corrugations. As it gets thin it breaks up, and when wet and dirty is slippery; it, however, requires little tractive effort, forms a jointless, impervious, sanitary, and easily washed surface, deadens the noise of traffic, is free from dust, and in temperate climates is practically indestructible, no matter what is the camber.

Some description of tar-bound roads is given here. It is based on English practice, as there is but little experience of them in the tropics. That practice should generally hold good there, although doubtless some modifications of it will be found necessary. In England the change from one class of surface to another has taken place only comparatively recently, and is mainly due to the advent of the motor car and to the dust nuisance produced by it. At first water-bound roads were tar painted yearly, but as motor traffic increased this was not found sufficient, nor was the use of hygroscopic chemicals successful; tar macadam was therefore laid, and has answered, as power propelled traffic still bears a small proportion to the total amount on roads. Nevertheless, the stress of traffic continues to increase; petrol-driven vehicles of constantly increasing weight are being put on the roads, and the most destructive form of these is the quite recently introduced fast travelling motor omnibus, which unduly stresses tar macadam. Water-bound roads tar painted yearly are, however, equal to carrying ordinary light traffic up to 350 to 400 tons a day. The annual maintenance charge for these is 3d. or 4d. per square yard per annum, whereas tarred macadam costs 3s. 6d. per square yard, and to be equally cheap must therefore have a life of from twelve to fifteen years, *plus* the time equivalent to the cost of its own maintenance; both kinds of surface must be kept sealed by tar coatings to preserve them intact. The increased cost of tar-bound roads is offsetted by the improvements effected by them, from which traffic greatly benefits and ordinary maintenance charges are reduced.

Water-bound roads are pervious, and this leads to greater internal abrasion of the metal when the surface is very wet or very dry; they cannot always utilise local stone, and they are deficient in binding power on which efficient road construction and maintenance greatly depend. Tar-bound roads are impervious, and they permit of the use of inferior stone, as the matrix holds the particles tightly and prevents sensible abrasion by its elastic quality, which gives it high binding power. They avoid the production of dust; they effect savings in scavenging (25 to 50 per cent.), watering (25 to 60 per cent.), and maintenance (50 to 60 per cent.); they distribute the weight of traffic better; they are more hygienic; they are noiseless; they permit of the adoption of a flatter camber (a steep camber makes the sides of the road slippery); their surface remains smooth; and they reduce the amount of the tractive effort of traffic. Their disadvantages are their extra cost, their lack of foothold on steep gradients, their slipperiness during frost, and the difficulty of patching them satisfactorily and of laying them when the weather is wet. It is not advisable to have the centre of the road tar-bound, and its side widths water-bound, as thus traffic will produce an unequal section, and dust will be brought on to the former from the latter.

Tar-bound roads are of three main descriptions:

(i) Tar sprayed or tar painted;
(ii) Tar macadam;
(iii) Pitch grouted.

The matrix employed may consist of—

(i) Tar products;
(ii) Natural asphalts;
(iii) Petroleum residuals.

Of these the last two are not much used on account of their expense, but this might be lessened by blending them with the much cheaper tar. The asphalt compound sets as hard as pitch, but is not brittle; it has the disadvantage of setting quickly, and thus requiring speedy rolling. Natural bituminous products are more uniform, and thus more reliable than tar and superior to it. Trinidad petroleum oil is the best artificial material, but is not so good as natural asphalt, which has greater stability, cementing power, and permanence, but is costly.

The English Road Board in 1911 issued directions and specifications relating to the tar treatment of roads.[1]

317. Tar.

Tar results from the destructive distillation of coal, and is a by-product of gasworks. It is unfortunately of a very varied nature, and different qualities of it are produced at the same gasworks, and still more so at different works. It should be commercially free from all volatile oils, ammoniacal liquor, dirt, and from an excessive quantity (i.e. more than 16 per cent. of its weight) of free carbon. It should have a specific gravity of from 1·18 to 1·20 at 59° F. (15½° C.), and should have added to it 40 to 45 per cent. of pitch, which remains after distillation at a temperature of 518° F. (270° C.). Crude tar, containing much water (which causes it to froth when heated), light oils, and naphthalene (over 7 per cent.) is bad. Distillation toughens tar, and it can thus be tempered so as to be not too soft in summer nor too brittle in winter. This toughening is due to ridding the tar of volatile products, and chemists should discover what should be added to it and what taken away to make it consistently the same in hot and cold weather. Tars which can withstand the heat of an English summer may not be able to remain plastic when subjected to tropical heat. Tar, even after distillation, is of a perishable nature, and will gradually deteriorate under varying atmospheric influences. Oxidation and volatilization will tend to deprive it of important constituents, and eventually reduce it to a hard and friable substance. Tar should have sufficient viscosity to enable it to resist penetration by superimposed weight at all atmospheric temperatures. A high-carbon tar is less penetrative into aggregate than a low-carbon one, but what the former loses in chemical purity as a bitumen it probably gains in mechanical strength. During distillation the free carbon is thoroughly and uniformly diffused throughout the tar, thus stiffening it and increasing its viscosity, and this improves its elasticity and power of recovery. The bituminous substance immediately surrounding the carbon particles has much greater binding power than that remote from them; the free carbon binds the oily and aqueous constituents of the tar together. The melting point of tars indicates their relative hardness and brittleness. The test for it is not much required in England, where the range of temperature is low, but will be of importance in tropical climates. Tars become brittle when they have given up the oils necessary to their elasticity, and thereafter cannot withstand heavy traffic. Asphaltic bitumen (obtained by the distillation of an asphaltic oil), which is more stable in respect to heat, is therefore better suited to such traffic than tar. A petroleum from Trinidad is recommended as the most satisfactory binding material yet discovered, and to be well suited to a hot climate.

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[1] Reproduced in Minutes of Proceedings, Inst.C.E. Vol. CLXXXVI, pp. 265–274.

318. Tar Painting.

Tar-painted water-bound surfaces are sufficient for ordinary traffic; although they are inferior in durability to the much more expensive tar macadam ones, they can be maintained in good order by fresh coatings at intervals, as these become necessary. The tar is put into barrels, which are distributed along the length of roadway, and from these it is emptied into tar boilers, in which it is heated; at the back of the boiler is a 2-inch discharge or outlet pipe controlled by a plug tap. The boiler is then drawn by horses at a walking pace, the tap is opened, the tar allowed to flow on to the road, and is at once "squeegeed" over the surface by men. On the wet tar a thin coating of ⅜-inch clean granite chips is spread, and at once rolled in by a steam roller. Six men working with one 320-gallon boiler will tar-paint 5,000 square yards in a day, including scarifying the surface and spreading the tar and chips.

To ensure the success of tar painting a good hard and well formed road surface is essential, such as one made of syenite or granite thoroughly consolidated and bound with clean granite chips. Before the tar is applied the surface must be quite dry and perfectly clean, i.e. free from dust, caked mud, and organic matter. The tar must be of the quality previously described (Art. 317), and should be heated to its boiling point and applied as hot as possible. On a newly metalled surface two coatings should be given, the first of 1 gallon of tar to 5 or 6 square yards; and the second of a gallon to 8 to 10 square yards. The pre-War cost was from 1d. to 1¼d. per square yard, or, say, £50 per mile of 18-foot roadway.

If the road surface is wet and dirty, the tar coating will not adhere, and if the tar is inferior, the coating will not be durable. To seal the surface and make it impervious a mixture of tar and pitch may be brushed into the interstices of the metal after the surface has been well rolled.

319. Tar Macadam.

Tar macadam differs from tar painting in that the entire road coating consists of aggregate thoroughly incorporated with tar, and the tar is not only on the surface of water-bound metal. The result is that in tar macadam the stones are solidly held together by an elastic and practically permanent binder, and their internal motion is almost entirely prevented; the little which does occur is not sufficient to abrade them. It is therefore a much superior form of construction, but is naturally also a much more expensive one; it should therefore be adopted only when the traffic conditions justify the extra cost. In both cases it is necessary that the under-road should be quite securely founded, consolidated, and drained.

In making tar macadam the approved aggregate should be graded for use in the different coatings, should be clean, free from dust and foreign matter, and should be heated on plates or in a revolving drum, to a heat not sufficient to injure the tar, and thoroughly mixed with it while hot. Some say the prepared material should be kept stacked in heaps for two or three months to season before it is laid; others prefer to spread it while still warm. The former procedure should, it is thought, secure a better consolidated and thus denser surface. For the first coating the aggregate should be broken to 2½-inch gauge, for the second coating to 1¾-inch gauge, and for the third coating half to ¾ and half to ½-inch gauge, the latter being reserved for finishing off. For the first two coatings 8 or 9 gallons of distilled tar should be mixed with 1 ton of aggregate, and for the third 10 to 12 gallons. The tar should be of the quality previously described (Art. 317). Just before being laid the mixture may be "freshened" by the addition of 2 or 3 gallons of tar per cubic yard. The thickness of the coatings when first rolled should respectively be 2½, 1¼, and 1 inches (including the finishing coating of ½-inch chips), and the whole should be finally rolled by an

8-ton steam roller to a total thickness of not less than 4 inches: a heavier roller may damage the aggregate. Some prefer to lay and consolidate the whole thickness as one coat, others to make the finishing coat 2 inches thick, as they consider a thin coat would wear and leave a rough surface; others say that the thin finishing coat will not separate from the lower coat if it is at once consolidated on that.

In regard to the nature of the aggregate some prefer hard, tough, well-broken, and screened blast furnace slag, which, as it largely consists of lime that quickly deteriorates when wet and exposed to the weather, should be kept dry until it is incorporated with the tar. Slag is preferred because it holds the tar better than does denser stone; for the same reason some consider a soft stone (e.g. limestone) better than a hard one (e.g. trap). Others think the aggregate should be of the best, toughest, and most durable stone procurable, such as granite or whinstone, as that will prove economical by securing a longer life. This would seem to be the sounder view, as if for any reason the slag particles became uncoated they would deteriorate. The metal used should readily assimilate the tar compound on its surface, and that compound should be crude tar boiled and thickened with pitch, and not of pitch and oil; the surface should be finished off with tarred chippings, not asphalt. Any deficiency in binding should be made good by altering the tar accordingly, or by treating the aggregate with a preliminary coating of bitumenous oil. In Toronto, which has a severe climate, several binders were tried, but did not give good results; eventually one of asphaltic bitumen, made by distilling an asphaltic oil, was used; this has the mechanical strength of coal-tar pitch combined with high ductility, which makes it very suitable for tar macadam for such a climate; for less severe conditions the bitumen might be blended with refined tar, which will cheapen it. Again, some consider that the mixing with tar should be done by hand to secure a better material; others recommend mixing by machine, especially when the tar used is a heavy one. The laying and consolidation is best done on a sunny day, but a little dampness is not so prejudicial as in the case of tar spraying.

For coating an old water-bound surface, that should be picked up so as to leave at least 4 inches undisturbed; the loosened metal should be screened, and the sound clean particles, mixed with fresh stone, should be utilised for the first coat, while the second and third coats should be made entirely of new stone, as they have to take the wear of the traffic.

320. Pitch Grouting.

Pitch grouting in America is called the "penetration method." It is carried out thus: A 3-inch layer of 2-inch metal is spread on the foundation, lightly rolled, and grouted with a mixture of standard pitch and sand, and is then thoroughly consolidated; on this is placed a 2½-inch layer of 1½-inch metal lightly rolled to an even surface, and then similarly grouted except that it is advisable to add a little cement to increase the toughness of the pitch. The surface is then sprinkled with dry chippings of the same stone, and the whole thoroughly consolidated to a thickness of about 4 inches. As required by the conditions of the traffic the total thickness may be made from 2½ to 5 inches, and the bitumenous grout may contain various proportions of sand, or may be used without sand.

The pitch grouting compound consists of "commercial soft pitch," to which are added 10 to 12 per cent. of tar oil (to increase its fluidity and power of penetration), and 45 to 50 per cent. by weight of well-dried sand; the mixture should be kept well stirred during use. The pitch should not contain more than 28 per cent. by weight of free carbon; it should yield no distillate below 482° F. (250° C.), and not less than 5 per cent. of it up to 600° F. (315° C.). It should be melted in boilers of not less than 2 to 3 tons capacity to about 300° F. (150° C.). The tar oil should have a specific gravity between 1·065 and 1·075 at 68° F. (20° C.), and should be free from naphthalene crystals, light oils, and water.

In re-surfacing a road the old metal is picked up, screened, and utilised with fresh material in the bottom coat. The top coat is made with the hardest and toughest stone available, as it has to resist the wear.

Pitch grouting properly carried out (i.e. made to penetrate thoroughly) is entirely successful, and is much used in America on account of its cost being lower than that of tar macadam. It is, however, inferior to that, as an excess of the bitumen grout is likely to be found at places, and to be brought to the surface by the heat of the sun. To prevent this, sand or grit must be applied to such places, or natural asphalt, which is not thus affected, used (either pure or diluted with 30 to 40 per cent. of partially distilled oil), instead of the artificial compound, especially in the tropics, where sand may not serve as a remedy for this defect.

PART IV. DISTRICT BUILDINGS.

CHAPTER XXVI.

DISTRICT BUILDINGS.

321. General Remarks.

As its heading implies, this chapter deals only with a limited class of building, and the limitation is still further narrowed by the confinement of the description to such buildings in ordinary tropical and sub-tropical areas, and intended for occupation by Europeans in the service of Government. Government buildings may be classed thus :

(i) Public buildings and offices ;
(ii) Public residential buildings (inspection quarters, etc.) ;
(iii) Private residential buildings.

The designs for (i) vary considerably in accordance with the different requirements and objects of the buildings, and are frequently fixed by standard plans so that detailed remarks are not made about them. It will suffice to say that before designing a public office the departmental officers concerned should be consulted as to the numbers of the staff and the nature of the accommodation for which provision has to be made. As official work has a tendency to increase as a district develops, an adequate but not excessive allowance should be made for the wants of the near future.

In regard to (ii) and (iii), which are dealt with hereafter, there is not so much scope for variety in design, and that will, as a rule, also be governed by standard plans. It will, however, be advisable to regard such plans not as immutably fixed, and from which no departure is permissible, but as general guides which under proper sanction may be modified to suit local conditions, or to secure improvements. This will give the designers more interest in their work, and should lead gradually to the evolution of the best types for the structures. With regard to (iii) it is usual and desirable to consult the first prospective occupier, as he may have useful ideas to communicate, and these should receive all the attention they deserve. It may, however, not be possible to meet his wishes, as they may be based on individual preferences; what has to be aimed at is to secure a design which will best suit the general convenience of all future tenants, and one of which the capital cost will not exceed that allowable under the rules in force respecting the amount of rent leviable, etc.

Not only has the design to meet domestic arrangements, but it must also suit climatic conditions, which vary greatly. For instance, in India there are four principal climates, namely, those which characterise areas situated in hilly regions, the hot plains to the north, the more equable plains of the centre and south, and the coastal districts. The first is temperate, and not greatly different from that of England; the second is excessively hot in the hot weather, and fairly cold in the cold weather; the third has less pronounced variation of temperature; the fourth has small variation in regard to temperature, but is distinguished by trying supersaturation of the air. Thus for the first, buildings may be more or less of the English type; for the second, special designs are necessary to secure protection from the powerful sun in one season and the cold in another; for the third, less sheltering arrangements will be sufficient; for the fourth, more airy treatment is desirable; for all, special provision is necessary to deal with the monsoon rainfall, and particularly for the last named, where it is intense. The descriptions below are based chiefly on experience gained in the Deccán, or upland, area of the Bombay Presidency, which generally has the third class of climate.

322. Design.

The engineer has to bear in mind that usually his training and experience do not fit him to compete in designing buildings with the expert architect, and as even the latter occasionally is unsuccessful in his designs, the former should recognise his own limitations. Although he may not be able to "design with beauty," he can "build with truth," and a truthful building will possess some degree of beauty owing to its simplicity and utility. He should remember that proportion, not ornament, is the basis of architectural design, and that the plan is the essence of it, and should be emphasised, or brought out, by the elevation. Absolute baldness should be avoided by retiring the minor parts and advancing the important ones slightly so as to secure ordered variation; the main structural lines should be sparingly ornamented; string courses, cornices, and simple mouldings round arch heads should be utilised to bind the whole together; and large masses of roof area should be somewhat broken up and diversified. Nothing, however, should be attempted merely for its effect and without a proper object in view, nor out of keeping with the nature of the design as a whole, e.g. a native rest-house should not assume the form of a Gothic church.

Buildings should be planned not only to secure the structural wants of the occupiers, but also to meet their climatic requirements. It is held by some that modern buildings for foreigners should be similar to the old ones for the natives of the country, but this opinion does not take into account the differences in the habits and physical temperaments of the two. A truer view to take is that the new-comers should study the work of the old residents, and combine with their own designs, or adopt, such portions of it as are suitable to their wants. If successful in their treatment, they also will leave their mark on the country, for buildings are the structural records of history.

Style is said to be the grammar of architecture, but each style has been gradually evolved from its predecessors, as architecture is essentially a process of development. A rigid adherence to a style peculiar to a European climate is not likely to lead to suitable buildings in a tropical or sub-tropical one, nor a strict attachment to an indigenous style prove comfortable to foreigners. In such altered conditions some departure from the prescriptions of old styles seems permissible, and this is admitted by architects; in fact, the process rightly carried out should lead to the creation of a new style. History shows that this course has been followed by the successive foreign occupiers of a country, and they have thus left their own impress on its buildings.

323. Plan and Elevation.

(*a*) *Plan.*—The first consideration, as stated above, is to design a suitable plan, and also one that is economically arranged. As an aid to this it is useful to cut out in paper pieces representing to scale the different rooms and to shift these about until the best general plan is obtained. Each individual room should have plotted on it to scale blocks representing the principal articles of furniture it is likely to contain, so that these may be disposed of in the most convenient way, and the room planned to give as much unoccupied space as possible. Through ventilation and good lighting should be secured independently in all rooms, particularly in the principal ones, and they should not depend on their neighbours for these, unless those are *en suite* and privacy is thereby not sacrificed. These desiderata depend chiefly upon the aspect; there should not be any difficulty in regard to light, of which there is usually an abundance in the tropics, which can be modified as required. Natural ventilation is due to the prevailing wind which there varies in intensity, but is generally constant in direction; thus buildings have to be built normally to that, and the tendency is therefore to erect them to a barrack-like design. To introduce variety in the plan, parts may be recessed and parts advanced, and the wings in a long elevation might be set at a very small angle to the main building. It is practicably impossible to secure an aspect which will suit equally well seasons of varying character. The one chosen should be that which will be best in the most trying season, which is generally the hot weather; the other seasons should be provided for by structural arrangements. This matter is dealt with in more detail in Article 332, which treats of verandahs. Similarly, when there are two conflicting conditions to be met, the design should provide for the one which is the more important of the two, or which occurs more frequently.

(*b*) *Elevation.*—In regard to the elevation most district residential buildings are single-storied, and thus present a somewhat squat appearance, the large roof area being superimposed on low verandah walls. This effect can be partially removed by constructing separately the roofs of the main building and the verandah with a narrow strip of walling between them, which can be pierced for clerestory windows. An upper storey has the following advantages:

It makes cooler the lower rooms which are occupied in the day-time;
It secures greater privacy, and more and purer air for the bedrooms, which would be located in it.

An upper storey has the following disadvantages:

The extra difficulty upstairs, where there is no town water supply, of getting water to the bathrooms and dealing with sanitation;
The extra expense involved by the necessity for the main and sweeper's staircases.

A private residential building in a town ought to have an upper storey to secure the above advantages, unless the excess cost is great; so also might a public residential building, especially in a hot district.

The main staircase, if placed in the building, will occupy an area on each floor equal to that of a small room, and is thus expensive. This position for it has, however, the following advantages:

It is protected from the weather;
It provides a passage through the building for servants;
It separates each floor into two parts, and thus gives quiet for an office room on the ground floor and privacy for a guest bedroom on the first floor;
It assists in the through ventilation of the building;
Under it on the ground floor linen, etc., cupboards can be constructed, and a boxroom at its back on the first floor.

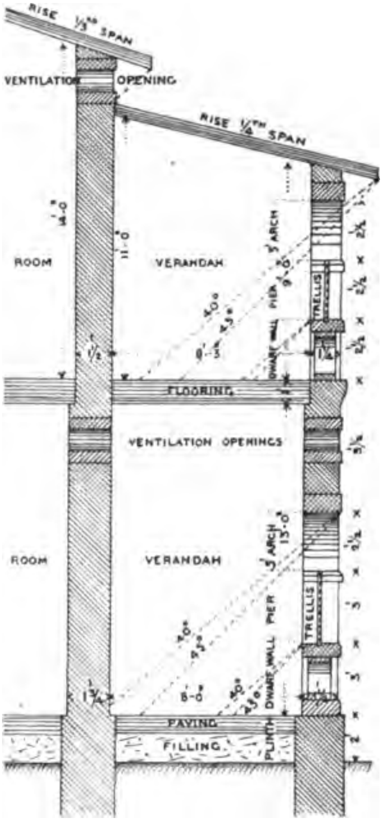
The main staircase will be cheapest if placed in the verandah, but there will secure only part of the last of the above advantages, and the first of them if it is enclosed by walling.

The sweeper's staircases present some difficulty in designing, so that they may not be too obtrusive. The different bathrooms to be served thereby should be grouped together as much as possible so as to reduce the number of these staircases or the length of the gangways from them.

As the visible exterior of a building in the tropics consists practically of verandahs, it is on their successful treatment that much of its architectural effect depends. The verandah must clearly show what it is, and not make the pretence of being the main building. It will best be built with arched openings ; however, these need not necessarily be continuous round the building, but some variety may be obtained by breaking them up by short lengths of solid walling where there are not openings (doors and windows) in the rooms behind. To keep out dust, animals, etc., shade part of the verandah floor, and form a base on which the verandah piers can stand, it is as well to have a front dwarf wall, say, 2½ to 3 feet high, on each floor ; this can be pierced to lighten its effect and to give floor ventilation. The verandah openings should not be too high, or else they will fail to shade the main building when the sun is low. It has been recommended that the intrados of the crowns of the arches, or the bottom of the entablature of square-topped openings, should not be higher above floor level than two-thirds the width of the verandah, and that the wall space above this level should be pierced by perforations. Probably a minimum height of the centre of the main openings should be about 8 feet, and for general appearance and convenience the minimum height of the openings at springing level should not be less than 5 or 6 feet. Another prescription is that the sun should not be able to strike the walls of habitable rooms at an angle steeper than 40° ; this might be modified to 45° (Fig. 198). For the same reason (to reduce the height of the arch heads) the

FIG. 198

VERANDAH OPENINGS



spans of the arches should not be large, and at intervals the arches may be grouped in sets to gain variety. The top of the verandah wall above or between the arch heads should be pierced by small circular or trefoil, etc., openings, or slits, so as to secure ventilation and top lighting. It is usual to fill in the arcades of residential buildings with teak trellis, which increases the shade and protection from glare, but decreases the lighting and diminishes the architectural effect by producing a flat surface without a shadowed recess in rear to set off the arcade or colonnade. "Chiks," or bamboo blinds, on the inside of the verandah wall might with advantage be substituted for these, as they can be rolled up when not required to shut out glare or wind, and thus more light and air will be admitted. In superior buildings the verandahs are sometimes glazed; not only does this produce a flat uninteresting exterior surface to the building, but in hot climates it increases the heat of the enclosed air, as it acts like a conservatory; it also prevents the perflation of the air and diminishes the lighting of the interior rooms. Such treatment is more suited to the coastal districts, as there it will protect the verandah from the driving torrential rains.

324. Construction.

(*a*) *General Remarks.*—It is held by architects that a building best composes with its surroundings if it is built of local materials; their use certainly should conduce to economy. The main building behind the verandahs does not require to be elaborately built, or of expensive materials. It will suffice if such materials are confined to piers, arch heads, string courses, etc., and the general walling constructed of plain brickwork or masonry properly laid.

(*b*) *Economy Practicable.*—Owing to the large area of the rooms in a residential building in the tropics, necessitated by climatic, domestic, and social conditions, to the considerable space occupied by verandahs, and to the extent of accommodation required for servants' quarters and outhouses, the cost of such a residence is much in excess of one that would be erected on the lines suitable for a temperate region. In order to reduce the amount it is desirable to effect economy by good planning (Art. 323) rather than by the use of cheap materials, which are likely to make the building uncomfortable and insanitary, and may prove costly in the end owing to the extra expenditure on maintenance which may thereby become necessary. Economy may also be attained by proper limitation of the sizes of the rooms (Art. 328), by reduction in the depth (or height), width, and cost of construction of foundations and walls (Art. 329), in the design of roofs (Art. 331), in the verandah area (Art. 332), and in the number, size, and description of doors (Art. 334) and windows (Art. 335).

(*c*) *Coolness.*—Coolness of construction must also be aimed at as far as permanence, comfort, and safety will permit. In the older buildings it was obtained without paying attention to these other desiderata. Massive walls of brick (often sun-dried—the coolest variety), or stone laid in mud, and mud plastered externally and internally, were built, while flat roofs were covered with mud several inches thick, and pitched ones were made of thatch. The mud construction was difficult to keep clean, required much repair, and was liable to be penetrated by rats, white ants, etc.; the thatch for all its coolness was undesirable, as it harboured rats and snakes, and was highly combustible in the hot, dry climate. It has been proposed to build walls hollow, or with non-conducting coatings, both of which measures will be expensive; and to construct flat roofs in reinforced concrete with interior air space, and pitched ones of patent heat-resisting tiles If the interior walls are kept well shaded, they will practically be as cool as it is possible to make them; flat roofs constructed as noted above should be an improvement; patent tiles usually look painfully new and obtrusive when first laid, and may weather so as to be unsightly; ordinary tiling, properly constructed, should suffice, and in cases of great heat might be whitewashed, as are native roofs, for this may lower the interior temperature by some 10° F. A good system of ventilation (Art. 325) is probably one of the most effective ways of producing the sensation of coolness.

325. Ventilation, Lighting, and Drainage.

(*a*) *Ventilation.*—In tropical areas ventilation is a matter of the first importance, for not only is it required, as in temperate climates, to change air vitiated by respiration, but also to produce coolness by inducing evaporation from the body; still, practically little has been done structurally to secure it, and dependence is placed chiefly on the open door and window and the punkah. An electric fan in the centre of a room simply causes the air to revolve, and does not change it ; such fans can, however, be used to force the air into or to exhaust it from a room, but this will be expensive for a residential building, and impracticable up-country, where electric mains do not exist. The common punkah is effective, and will change the air. It is, however, unsightly and cumbrous, tends to darken the room, and usually requires a puller to work it. Ordinary ridge ventilation is out of control, and may admit dust and rain. Upcast shafts have been recommended, as they automatically cause a moderate movement of the air when they are heated by the sun or have lighting (and thus heating) arrangements placed vertically under them. For private residential and public buildings they might be of some height, and the various rooms might be placed in communication with them by light horizontal air shafts. For district inspection buildings each main room might have on it a sheet-iron upcast shaft a few feet high, painted black to make it get heated, so as to increase its extracting power, and might have a protecting cap at top to prevent rain from descending down it (Fig. 207, p. 816), or, better, a revolving cowl still further to aid that power.

High rooms give a sensation of coolness, and they undoubtedly allow a greater space for heated vitiated air to accumulate at the top ; this, however, will eventually cool and descend by vertically circulating currents. High rooms are also, of course, more expensive to construct than low ones. For these reasons it is best not to have very high rooms, and to provide openings near the top of the outer walls for the escape of the heated air (Fig. 198, p. 795). Door and window heads (Arts. 334 and 335) can also be utilised to admit air or to let it escape at a high level.

(*b*) *Lighting.*—The essentials of good lighting are that it should be—

(i) Sufficient everywhere in the rooms ;
(ii) Not excessive so as to produce glare ;
(iii) Disposed as required ;
(iv) Under a certain amount of control or adjustment.

As to (i), there is generally throughout the year in the tropics abundance of light available for rooms not shielded from the heat by verandahs, but verandahs greatly lessen the amount of such light. To increase the lighting of rooms thus protected, the verandah wall above the main openings should be pierced with minor apertures, and, where desirable, clerestory windows or openings should be constructed above the verandah roof.

To reduce glare (ii), which causes discomfort, the bottom panes of windows and glazed doors can be filled with frosted glass; the lower part of the verandah openings can be closed by pierced dwarf walls; and on these trellis work can be erected up to, say, 6 feet above floor level. Top lighting by clerestory windows or skylights will diminish glare until the rays of the sun enter directly through them, unless these can then be shut out by blinds. Such lights, however, admit heat throughout the day, but this may be desirable in the interest of ventilation.

In regard to (iii), dining-rooms require the centre to be well lit, and sitting-rooms the sides, i.e. the places where the occupants will usually sit; in bedrooms, for the sake of privacy, the beds should not be exposed to external view, but for that of coolness should, when necessary, be in a current of air; doors and windows should be spaced accordingly. Writing tables should have a left-hand light, and a blank wall should be opposite the writer.

The amount of light admitted (iv) can be controlled to a certain extent by the opening or closing of doors and windows (clear sheet glass obstructs about 20 per cent. of the light); also by having parts of the verandah trellis made in leaves which can be opened; or by means of roller blinds, in substitution for, or in addition to, the trellis. Sunshades protecting external windows from the sun can be made with their roof boards adjustable to different angles as required by the degree of light existing.

(*c*) *Drainage.*—Drainage for the buildings under considera tion will be limited to surface drainage, and occasionally to subsoil drainage down to a small depth. The ground all round a building should ordinarily be sloped off for at least 10 feet at a slope of about 1 in 10, and the drainage led away by tiled or concrete gutters for, say, another 20 feet, if the natural slope of the ground is flat. Should the ground surface be sloping and the subsoil be of fissured rock, this may lead to the saturation of the area underlying the building by upstream underground percolation, which should be prevented by excavating close to and all round the structure a trench 2 or 3 feet wide and deep with a good outfall, and filling in the excavation with open porous material cased on the sides and top by similar but fine material to prevent clogging by silt, which might otherwise be carried into the filling. The drainage from the outhouses, and particularly that from the kitchen and stable, should be led away from the buildings in semi-cylindrical glazed earthenware tiles, or in small, ovoid-shaped, smooth-faced, self-cleansing open concrete drains cement-faced. The well should be located where no contaminated drainage can percolate into it.

As the fever-carrying Anopheles mosquito breeds freely in any collection of stagnant water, and usually does not fly more than 200 yards from a breeding ground, it is essential to drain or fill up all pools, etc., in the neighbourhood of a building, and to see that none are formed by sullage water. Within that distance borrow pits on the roadside should be filled up to such a level that they may automatically drain off, and scour holes in roadside gutters should be eliminated by dressing off or filling.

The site plan of a building should show the north point, the directions of the prevailing wind in the principal seasons, the direction of the flow of surface drainage, and any drainage arrangements proposed.

326. Location of Buildings.

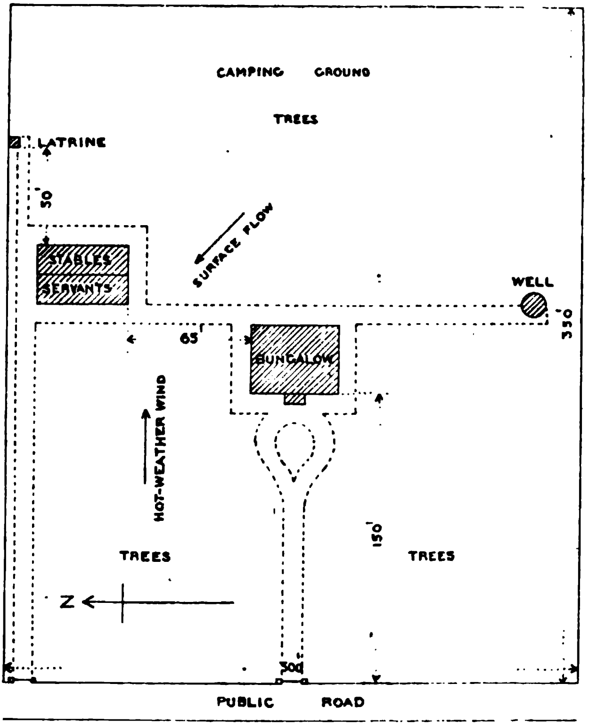
The main building should face the prevailing wind in the hot weather. To secure privacy it should not be overlooked by, nor be to the leeward of, the servants' quarters, which for this reason should be placed end on to it, and should have a separate exit path to the main approach road out of the grounds (Fig. 199). Of the servants' quarters the cook-room should be nearest to the main building, so that meals may be served hot; for a private residential building the cook and lamp rooms may be in a separate block, say, about 15 feet from the main building, and connected to that by a covered passage (Fig. 200, p. 802*a*). To secure quiet when this is arranged, the quarters for the other servants should, if possible, not be within 100 feet of that building, and otherwise not much less than 75 feet from it. If all the quarters are in one block, the cook-room should be next to the main building.

For a private residential building the stables should be in a separate block well away from it (Fig. 201, p. 802*a*) ; for a public one, for the sake of economy, they should be at the back of the block of servants' quarters (Figs. 199 and 202, p. 804).

The servants' latrines should be placed out of sight on the side of the servants' quarters remote from the main building, and to the leeward of these. Ordinarily, they should not be less than 50 feet from the quarters, but may be somewhat closer in rainy localities. The surface flow from them should be away from the well, but if that cannot be arranged, the latter should be excavated at least 100 feet away from the former. It should, if possible, be located where the most water is required, e.g. the garden.

FIG. 199

SITE PLAN OF INSPECTION BUNGALOW



To secure privacy and quiet a public residential building should be placed from 2 to 3 furlongs to the windward side of the village, etc., i.e. neither too near nor too far from it, as supplies have to be obtained therefrom. If practicable, for the same reason, the grounds should be retired a little way from the main road, and should be on its windward side. The main building should be set back about 150 feet from the front of the grounds, and the outhouses kept to one side of it. The back and front of the grounds should be planted with good shade and fruit-producing trees; so as to form camping grounds (Fig. 199). As pretty a view as possible should be obtained, and also a site furnishing a good water supply by means of a well. The boundaries of the grounds should be properly demarcated by stones.

When a large number of inspection bungalows has to be built, these should be distributed over the district, so that with the existing buildings they may serve the interests of travelling officials of all departments in the most economical and convenient way; for this purpose they should be spaced at regular intervals generally along made roads and near principal villages and towns.

327. Location of Rooms.

Fig. 200 is a plan of a large residential bungalow, and Fig. 201 that of a small one. In such buildings it is advisable to have the drawing-room at one end with a separate verandah and the entrance porch in front of that; thus the rest of the rooms will be retired and private in respect to visitors. Next to it will be the dining-room with the godown (storeroom), and dispense (pantry) in convenient proximity. At the other end in the large building will be the occupant's private office, room or study, and in the small one the bedrooms, both in the most secluded position. In England the front door is generally placed in the centre of a house, but there usually all the private rooms, bedrooms, etc., are on upper floors, and each floor has a central passage giving independent access to each room. In the large bungalow the bedrooms are placed upstairs, and the guest-room is divided from the others by the staircase (Art. 323 (*b*)). In both designs the minor rooms —dressing, bath, etc.—are placed at the back of and in communication with the main ones. There they take the

place of a back verandah, and being principally on the east or cooler side, and being utilised only for a short time, chiefly early in the morning or late in the evening, will not be unduly hot (Art. 332). The bathroom doors should be at the back, so that the sweeper has not to come to the front.

Fig. 202 is a plan of a small inspection bungalow affording temporary accommodation for a single officer, or for two on occasion. The entrance is here in the centre to secure privacy to the side or bedrooms. In the back verandah are the minor rooms to the east side. Some prefer plenty of verandah space for the storage of travelling kit; this can, if necessary, be given cheaply by forming a stacking platform and obtaining protection from rain by a cheap, light roof carried on light supports (Fig. 203).

Fig. 203 is a plan of a fair-sized travellers' bungalow, which may be occupied at the same time by several persons who are strangers to each other. The plan makes provision for two married and two single quarters (together convertible into a third married quarter when necessary), each with an entirely separate entrance, thus securing as much privacy as is practicable to each set of rooms. The design lends itself to expansion or contraction as may be necessary. It would be improved by making the central bathrooms of the married quarters project from the rear of the building, converting them as drawn into bathrooms for the single quarters and changing the bathrooms shown for these into dressing-rooms for them.

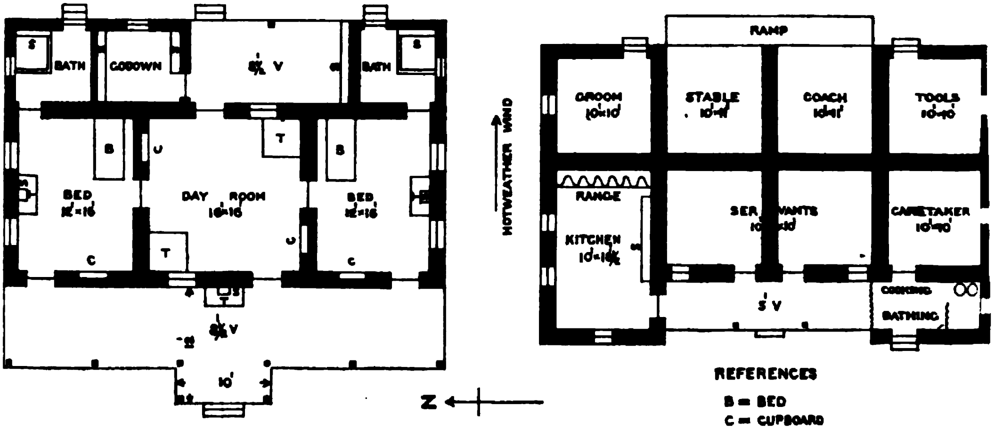
328. Sizes and Numbers of Rooms.

The sizes and numbers of rooms naturally vary with the requirements of the occupants, but the following descriptions will, it is thought, meet average wants, and it is these that a public residential building has to satisfy, and not unusual ones, which, if provided for any particular case, might not suit ordinary ones. The sizes are larger than what would suffice in England, but that is because more area is required in tropical and sub-tropical countries to meet climatic and social conditions. They may need small modifications to suit the design as a whole. In the interest of economy care should be taken to reduce the floor area as much as practicable without loss of necessary comfort.

(i) *Dining-room.*—For a fair-sized dining-room in a

FIG. 202

SMALL INSPECTION BUNGALOW



BUNGALOW

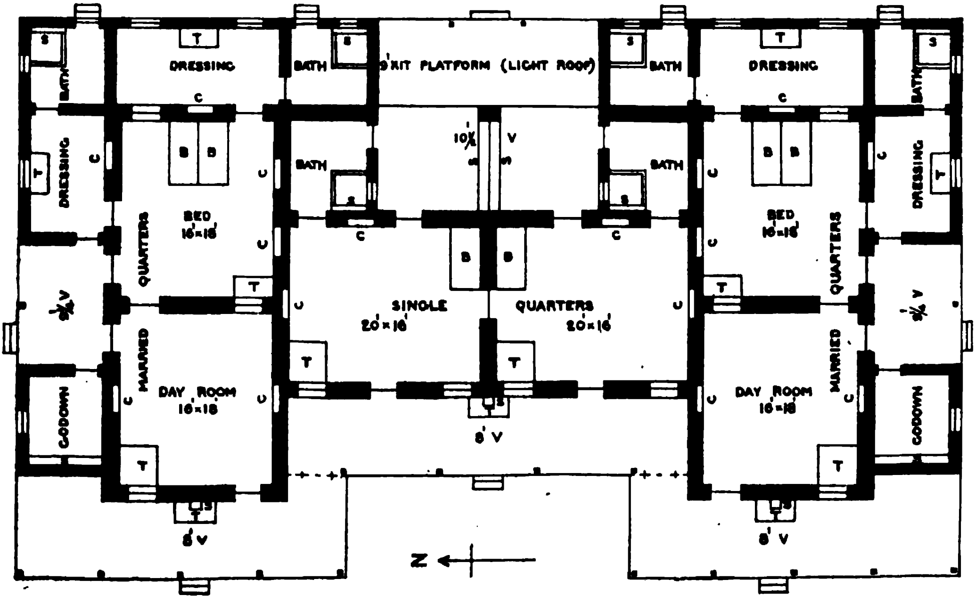
OUTHOUSES

REFERENCES

B = BED
C = CUPBOARD
S = SHELVES
T = TABLE
V = VERANDAH

FIG. 203

LARGE TRAVELLERS' BUNGALOW



residential bungalow to seat twelve persons the minimum lengths and widths required are for:

	Length. Ft.	Width. Ft.
The table	10	5
Chairs (2 feet on each side)	4	4
Circulating space (3 feet on each side)	6	6
Large furniture along walls	4	3
Total	24	18

A smaller room might be 20 feet by 16 feet, which will be a good size for the main room of a large inspection bungalow; for an ordinary inspection bungalow that might be 16 feet by 16 feet, and not less than 14 feet by 14 feet.

(ii) *Drawing-room.*—This will usually be about the same length as the dining-room, and it may be a little wider than that. These two rooms will generally be in connection with each other, and leading out from the drawing-room may be a small boudoir or lady's sitting-room, which will be a convenience.

(iii) *Bedrooms.*—For a residential bungalow a large-sized room would be 18 feet by 18 feet, and a fair-sized one, 16 feet by 16 feet. For an inspection bungalow a fair size would be 16 feet by 12 feet, and the minimum size 12 feet by 12 feet. For the larger buildings, two, three, or four bedrooms, and for the smaller ones two might be provided.

(iv) *Dressing-rooms.*—The minimum width desirable is 8 feet; 10 feet is much better, as with this width the room can, on emergency, be used as an extra bedroom. The length should not be less than 12 feet. One such room should be provided for each ordinary bedroom, and two for main bedrooms in a residential bungalow.

(v) *Bathrooms.*—One such room is required for each dressing or bedroom; where the former is provided, the bathroom should lead out from it, and not from the latter direct. The minimum internal dimensions of the bath-place are 4 feet 6 inches by 3 feet 9 inches, and the external ones 5 feet by 4 feet 3 inches (i.e. should it be enclosed on two sides by a dwarf wall, which might be 6 inches wide and 6 inches high, with its top chamfered 1 inch on each edge). Space may be saved, when the bathroom floor is raised sufficiently, by recessing the bath-place 6 inches deep in it, thus dispensing with the necessity for dwarf walls round it. For the sake of cleanness the floor of the bath-place should be given a gentle fall to the drain, and it and the side walls should be plastered with cement well polished, and should not be whitewashed, as that will dirty the feet of the bather. A bath-place should not drain to the front of the building. The drain should be formed of semi-cylindrical glazed earthenware tiles or of concrete, half ovoid in section, and cement plastered; it should lead well away from the building, through the wall of which the waste water should be passed in a galvanised pipe 1½-inch diameter.

(vi) *Storeroom* (*Godown*).—For a residential bungalow the minimum width is 8 feet and length 12 feet; for an inspection bungalow, 6 feet and 10 feet will suffice.

(vii) *Pantry* (*Dispense Khana*).—For a residential bungalow the minimum size desirable is 12 feet long by 8 feet wide. A good plan is to substitute for it a servants' room, 12 or 15 feet square, projecting from the back verandah, and formed by dwarf walls, with trellis work on top and a light roof (Fig. 201). For an inspection bungalow 10 feet by 7 feet will be a good size.

(viii) *Verandahs*.—For ordinary verandahs of residential bungalows 8 feet is a fair minimum width (10 feet is, of course, better). This width might be allowed for inspection bungalows, and for them the minimum may be 6 feet. For inspection bungalows in hot districts an additional floorless outer verandah, or sunshade, with a cheap light flat roof supported on posts, gives increased protection from the sun, as it shades and thus keeps cool the outer walls of the true verandah, which would otherwise get hot and heat the main building (see Fig. 207, p. 816). This detracts from the architectural appearance, so that for it in residential bungalows in hot districts similar protection may be obtained by "chujjas," i.e. wide projecting slab sunshades resting on stone brackets, or by carrying the verandah roof, say, 3 feet beyond its wall and supporting the projection by brackets or struts.

(ix) *Servants' Quarters, etc.*—The minimum sizes and numbers are for:

	Residential.			Inspection.		
	Number.	Length. Feet.	Breadth. Feet.	Number.	Length. Feet.	Breadth. Feet.
Cook-room	1	16	12	1	15	10
Lamp-room	1	6	9	—	—	—
Servants' quarters	4 to 6	11	9	3	10	10
Stable stalls	2	11½	10	1	11½	10
Coach-house	1	11½	10	1	11½	10
Tools and plant and caretaker	—	—	—	2	10	10

For residential bungalows the quarters as proposed are each 11 feet by 9 feet instead of 10 feet square, as usual, so as to give a greater frontage. A verandah 6 feet wide might be constructed in front as a trellised porch, and corrugated iron partitions fixed between the quarters so as to increase the comfort and privacy of the occupants. In this verandah a cooking- and a bath-place for each might be provided. A separate detached bathing-place for all in common is, however, a better arrangement.

(x) *General Remarks.*—When designing rooms, the large articles of furniture should be plotted in them with respect to doors and windows, cupboards, shelves, etc., so that the most convenient arrangement for all may be obtained.

Doors and windows should be placed near the corners of rooms so as to distribute light and ventilation, to allow for the minimum space for traffic across the room, and to provide as much blank wall space as possible for cupboards, furniture, etc., between them.

Windows should give a left-hand light to writing tables. The leaves should open outwardly, so that they will not knock over articles placed on the window-sills.

The leaves of doors should open inwardly, so that they may be secured from the inside, and so as when partly open to disclose as little of the room as possible from the outside. When rooms are *en suite*, and privacy is desirable for the inner ones, the front and partition doors should not be opposite to each other, so as to avoid a through view from the outside when the outer ones are open.

Economy can be attained by making the numbers and sizes of the rooms as small as is consistent with reasonable comfort. The areas of the rooms may be somewhat reduced by constructing recesses in the walls to take the larger articles of furniture (cupboards, etc.). The heights of the rooms can be lowered slightly beyond the usual allowance. Although high rooms give a sense of coolness, the modern practice in England is to depend more on frequent changes of air in apartments than on the volume contained in them. An ordinary small room need not be higher than 12 feet to the rafter wall plate line, and an ordinary large one 14 feet. Generally, the heights of rooms may be for—

	Ground Floor. Feet.	Upper Floor. Feet.
Large residential bungalows	13 to 15	12 to 14
Small residential bungalows and inspection bungalows	12 to 13	10 to 12
Outhouses and minor rooms in bungalows ..	7 to 8 at eaves.	—

329. Walls.

(*a*) *Foundations.*—The foundations should be regulated in depth and width in accordance with the weight of the walls they have to carry and the nature of the subsoil which has to support them. To ascertain that nature trial pits should invariably be dug, and should extend a few feet deeper than the originally proposed foundations to show what underlies them, and if this necessitates a change in their design. When the ground is side-long, the foundations may have to be stepped. Before work is started, any stepping required, the height of the plinth, and the amount of general surface dressing to be excavated or raising to be done, should be determined in office from the information given by trial pits, and sections of the ground with the subsoil strata plotted thereon.

Where the foundations rest on hard material at a considerable depth, the walls below ground level should be carried down with small offsets projecting at long vertical intervals, so that the substructure will not be unduly thick, nor the foundation too wide (Fig. 204). If good founding material cannot be met at a reasonable depth, the foundations should not be carried down very far, as that will only surcharge the bed unnecessarily, but the substructure should be widened out quickly, so as to spread the weight over a large area. Should the natural foundation consist of black "cotton soil" of great depth, the wall foundations should be carried on a good thick layer of well-rammed muram, quarry spauls, metal, etc., and the sides of the excavation trenches well packed with the same material to prevent the shrinkage when dry and the

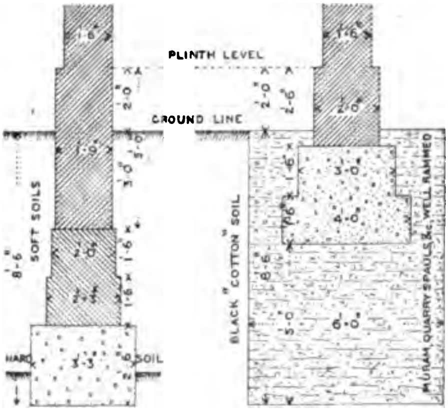

DEEP FOUNDATIONS

FIG. 204 ON HARD SOIL

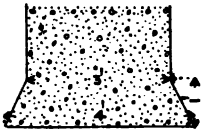
FIG. 205 ON BLACK SOIL

expansion when wet of the black soil from affecting the walls (Fig. 205). In such a case for an important building some recommend that the whole area covered by it should be thus treated; others, that the walls should be carried by an arched and inverted substructure of some depth. It is, of course, highly desirable whenever practicable to reject a site offering bad foundations, and to select instead a place giving good ones.

The base of foundations should be of concrete of sufficient thickness and width to carry and distribute the load of the superstructure safely. The width of the base can be cheaply and efficiently increased by undercutting the sides (Fig. 206) just before the foundation trench is filled in.

FIG. 206

WIDENING FOUNDATIONS



(*b*) *Plinths.*—Plinths should not be less than 2 feet high for residential buildings, 1½ feet for inspection bungalows, and 1 foot for servants' quarters. Where the ground is damp these heights should be increased by not less than 6 inches, and the floors should have under them well consolidated, clean, dry filling carried up to within 6 inches of the finished surface. If white ants are feared, the bottom of the filling should be formed of clean sand 6 inches thick, to which might be applied a white ant solution (arsenic and aloes, copper sulphate, solignum, or sheep-dipping composition). In bad cases of damp or white ants, bastard asphalt (Art. 330 (vi)) 6 inches thick might be laid at the bottom of the filling. A damp-proof course (asphalt, slate, or cement) should be laid 6 inches above ground level in damp situations where moisture is otherwise likely to rise into the walls.

(*c*) *Superstructure.*—The thickness of superstructure walls should be regulated in accordance with their length, height, and the weight they have to carry. Extra thick walls are expensive, as they unnecessarily increase not only their own areas, but also those of foundation work, verandahs, and roofing. Minor rooms can have their short interior walls of thin brickwork strengthened by hoop iron laid horizontally at vertical intervals in the courses. Partitions in residential bungalows can be made of reinforced concrete or framed slabwork, and in inspection bungalows of corrugated iron.

Roof trusses can be carried on pilasters, and the general wall reduced in thickness correspondingly.

Inner walls and plinths concealed from view should be built of cheaper masonry or brickwork than that of which visible external ones are constructed. As walls are thin, they should be built homogeneously, and not with a fine face and rough backing, unless they are low. The walls of main buildings should be laid in lime mortar; those of servants' quarters and outhouses may for economy be laid in mud and pointed externally in lime mortar.

The external edges of walls should be truly straight and vertical, and when of stone masonry should be finished off with drafts $\frac{3}{4}$ inch wide; wider ones look coarse. Arch rings of door and window heads may be emphasized on the exterior by being made to project $\frac{3}{4}$ inch from the face of the wall, and their keystones $\frac{3}{4}$ inch more; greater projections look clumsy. The openings for doors and windows and for recesses should have their internal edges rounded, or better, chamfered off, and should be set in lime mortar (preferably mixed with a little cement), to prevent their being chipped off; these edges should be perfectly sharp and true. Residential rooms should have their walls lime plastered, and the plaster should be finished off with long steel floats so as to get an even surface, which it is impossible to obtain with the small trowels generally used. A recessed date stone giving the year of completion should be fixed unobtrusively in the centre of the front of a building—generally under the verandah roof. Number stones giving the number of each block on the general register of buildings should be built in where they will easily be found, probably at the back of the building near a corner, and from 2 to 3 feet above ground level will be a good situation. The figures should be from $2\frac{1}{2}$ to 3 inches high, and cut V-shaped in solid block lines about $\frac{5}{16}$ to $\frac{3}{8}$ inch thick.

330. Floors.

(*a*) *General Remarks.*—Rooms in residential buildings should have floors of cement concrete, which can easily be kept clean, and, being smooth, will not wear out carpets placed on them. In some modern hospitals marble veneering has been laid, which seems a needless expense; moreover, such floors have thus many joints which may harbour dirt and disease germs, and the surface is apt to wear. A cemented floor seems preferable in ordinary cases, as it is cheaper, jointless, and can be washed with disinfectants when desired. Specifications for such floors are given below.

Rooms in public offices and verandahs in them and residential buildings on which there is much traffic should have 1½-inch paving slabs laid on 4½ inches of lime concrete.

Upper floors should be of fire-proof construction.

Floors in damp situations should have their beds formed as already described (Art. 329 (*b*)).

Floors of servants' quarters and of outhouses should be of bastard asphalt, as specified below, for this material is durable, clean, dustless, and white-ant proof.

Before a floor is constructed, the joints of the walls against which it abuts should be well raked out, so that the floor may be solidly united to their masonry in order to prevent white ants finding their way up the junction between the two.

(*b*) *Specifications*—(i) *General.*—For all the specifications given below before the flooring is laid its bed must be carefully levelled and thoroughly consolidated. In the surface Portland cement layer, instead of small-grained sand (which may cause abrasion to take place), it is better to have fine dressings from stones or particles having a minimum length of about one-third of an inch, which will not lead to abrasion, and will bind the cement together, thus preventing the formation of cracks by expansion and contraction due to variation of temperature. When the cement skin is to be made in alternate blocks or strips, these should be formed by means of battens of the required height, with their tops set truly at floor-surface level, soaped to prevent the adherence of mortar, and removed before the remaining blocks or strips are laid. The ordinary concrete should be mixed on boards, laid in place, and well rammed as usual. The cement mortar for the skin should be as dry as possible to allow it to be smoothened by a wooden float; for completion it may be sprinkled with neat cement and rubbed over by a float. Finally, all should be kept moist for, say, three days by wetted grass, and then flooded 1 inch deep with water from seven to twelve days. The cement skin should be of some thickness to enable it to withstand pressure coming on it—one only ⅛ inch thick cannot resist wear and should not be laid; the skin should be formed as soon as possible on the under layer, so as to unite firmly with it. If a polished surface is likely to be too slippery, a low diaper pattern can be imprinted on the surface directly after it has been floated.

(ii) *Ceylon, No.* 1.—The concrete flooring, 6 inches thick, to be made thus:

1 Cement to 1½ sand to 5¼ metal (1½-inch gauge).

On this to be formed a skin ½ inch thick of 1 of cement to 1 of sand. If the skin is laid on the concrete as soon as that is finished, the two will adhere; if the concrete is first allowed to set, the skin will separate from it.

(iii) *Ceylon, No.* 2.—On the prepared foundation a 6-inch layer of small broken brick to be laid and well rammed so that its surface is 4 inches below finished floor level. On this 3 to 1 cement mortar is to be spread, and at once on it a layer of wetted bricks laid flat, and breaking joint with wide joints, is to be pressed down so that the mortar is squeezed to fill the joints about half-way up. The surface is then to be rendered to floor level with a skin of 1 to 2 cement mortar ½ inch thick, laid as dry as possible and completely filling the joints of the brickwork, and this is to be floated over until it is quite smooth.

(iv) *Bombay.*—A layer of ordinary lime concrete 4½ inches thick to be formed thus:

1 part of mortar (1 lime to 2 sand) to 2 of clean trap metal 1½-inch gauge.

This to be kept well watered for about ten days until it has set.

On top of this to be laid cement concrete 1½ inches thick and as dry as possible, formed of:

1 part of cement to 1 of large sand and 2 of trap metal ½-inch gauge.

The sand and the metal to be washed clean of all dust, clay, and loamy or organic matter before being mixed. The concrete to be laid in place, levelled with a wooden float, and trowelled over. If practicable, this to be done in one operation, but for large areas the skin may be formed in alternate strips about 4 feet wide.

(v) *Jabbulpore.*—A layer of lime concrete 3 inches thick to be formed as usual, but with 10 per cent. more mortar than in ordinary specifications. On this a layer of well-burnt brick broken to 1-inch cubes previously soaked in water for six hours to be laid at once with the pieces closely packed together, and this to be rolled by a one-third ton hand roller until the cubes are well embedded in the concrete and the whole is hard and unyielding. On this to be laid as soon as possible and within three days in alternate squares from 3 to 4½ feet side a layer of cement concrete ¾ inch thick formed thus:

> 2½ parts cement, ½ of slaked lime, 3 of large sand (⅛-inch mesh),
> 4¾ of ½ inch and 4¾ parts of ¼-inch aggregate.

The aggregate and sand to be washed thoroughly first, and the whole mixture applied fresh and then rammed. Thereafter the surface to be polished with polishing trowels, and neat cement to be sprinkled on as required. If the surface is to be stone-polished and coloured, two coats of colour to be put on and worked in to the still damp surface and polished by special polishing stones of pumice 9 inches × 10 inches × 3 inches fixed to 6-feet wooden handles. Before the alternate squares are filled in, the vertical edges of those already laid to be whitewashed, to prevent the two sets adhering to each other; the joints between the two will when finished show as very fine lines.

(vi) *Bastard Asphalt.*—The asphalt to be made of 1-inch cube metal well boiled in tar of a moderate consistency, so that all may adhere properly, and to be laid 3½ inches thick in strips corresponding to the width of the roller by which thorough consolidation is to be evenly effected while the material is still hot; the roller to be kept well wetted, so as not to lift the flooring. On top of this to be applied hot and spread evenly a layer ½ inch thick of:

> Small stone chips, or coarse gravel, or pounded hard burnt brick—2 parts;
> Slaked lime—1 part;

boiled in a mixture of pitch, 1 part, to coal tar, 2 parts. The surface of this to be covered with ¼ inch of very fine sharp sand, and then to be well rolled.

331. Roofs.

(*a*) *General Remarks.*—Owing to their large area and the necessity for making them cool as well as water-tight, roofs are an expensive item of construction. The more water-tight the roofing can be made, the flatter may be its slope, and thus some reduction in cost can be effected; an ordinary slope for a tiled roof is one having a rise equal to one-third of the span. Trusses are costly, and, as they are generally exposed to view, are unsightly; the rooms should therefore be planned so as to avoid them as much as possible. For small spans collar-beam trusses can be substituted for king-post ones, and with advantage to appearance. The purlin form of construction is the cheapest, and also looks well; it can be used for small spans. For large spans and long rooms the length might be broken up into bays by masonry arched ribs supported by pilasters, and these would carry the purlins and ridge, or those might be formed of strong rolled steel joists enclosed in wire netting plastered, and the masonry ribs omitted. Roofs over verandahs and minor rooms might be flattened a little, say, to a rise of one-fourth of the span; this will improve the appearance of the building and lessen the height, and thus the cost of the main walls. All but the cheap roofs of outhouses should have squared teak rafters and battens, so as to give a true and regular slope and uniform resistance to the weight, and so as to present a neat appearance.

Roofs have generally plain unbroken surfaces; if, however, they are diversified by dormer windows, minor gables, etc., care should be taken not to have many valleys, and especially not over important rooms, as they are often the source of leaks. Conical ends cannot well be made with ordinary tiled roofs, as the tiles have to be cut; instead of them the ends should be polygonal to avoid this difficulty. If there are verandahs in continuation of them, the verandah space, and thus the cost, is increased by their concentric projection.

A cool roof is a necessity in tropical and sub-tropical areas. A galvanised iron roof has been found to be from 10° to 20° F. cooler when painted white than when left of its natural colour. To paint such a roof red in order to make it appear like tiling is architecturally wrong, does not produce the desired effect, and does not add to its coolness. A dark-coloured tiled roof will also be made cooler by whitewashing the tiles with insoluble whitewash, and this will also tend to make them more water-tight. Where minor rooms take the place of verandahs on sides of a building exposed to the sun, they can be shaded by extending the eaves of the roof, say, to

3 feet from the wall and supporting the extension by struts or brackets.

It may be noted that a thin domical or barrelled concrete roof gets very hot, is apt to be porous and leak, is likely to crack under the heat of the sun, and to be costly to construct and maintain.

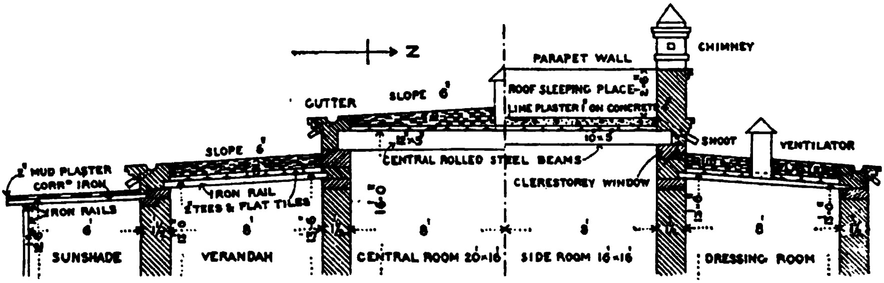
(*b*) *Roofing*.—The indigenous roof covering in the Deccán was formed of small flat tiles, but these are now giving place, even in native buildings, to half-round ones set in pairs—one pair for single tiling, and two pairs superimposed for double tiling, which has thus a fair amount of enclosed air space. The objections raised to such tiles are that they are leaky, and are apt to be displaced by animals and birds; both these defects would be lessened were the tiles made better and longer —12 to 16 inches instead of 9 to 10 inches long. The longer tiles would not only be heavier, but would involve far fewer joints, which are the principal cause of leakage. This might be further lessened by making the channels of the lower layers of the sets of tiles more water-tight by—

(i) Tarring with hot tar the inside of the tiles when heated by the sun;
(ii) Dipping the tiles into unwashable whitewash (3 of quicklime to 1 of common salt (by weight));
(iii) Dipping the tiles into a solution of 1 of alum to 2 of hard soap (by weight).

A vitrified salt glaze would be still better, but is beyond the power of local potters. The advantages of country tiles are that they are locally made, cheap, and easily replaceable, and form a cool roof; every endeavour should be made to remove their defects. A good pattern is the Belgaum roofing, which consists of teak battens 2 × ½ inch, placed 2½ inches apart clear, on which are laid flat tiles 4½ × 6 × ½ inch, with the edges rubbed to make close joints, soaked in pure white lime of the consistency of cream, and then dried; on these is spread ordinary mortar, ½ inch thick, on which is placed a single layer of half-round tiles, 13½ × 4½ inches, or still longer. The battens and flat tiles might be replaced by metal lathing and plaster, or wire netting and plaster, laid direct on the rafters. Mangalore tiling is much used in modern buildings. The tiles are flat, 16 × 9¼ inches, have interlocking projections and recesses on the under side, and drainage channels on the upper side, and are laid on 1×1¾-inch battens. Their advantages are durability and water-tightness; their disadvantages are their expense, their non-local manufacture (entailing the maintenance of a stock for repairs), their glaring appearance when new, and unsightly weathering when old, their liability to be stripped by the wind, and their forming a hot roof. The last two defects can be met, the first completely and the second partially, by fixing a planked ceiling below them, but this adds considerably to the expense. There are other patent interlocking tiles on the market, and ones made of asbestos are recommended for their coolness, but they have not yet been adopted up-country. Galvanized corrugated sheets are used for roofing small buildings, as they can be laid cheaply and quickly. Their disadvantages are that they form hot roofs, are noisy, not water-tight nor durable, as they are apt to rust at the rivet holes, and may be stripped off by high winds. They can be made cooler by covering them with tiles, or fixing a teak ceiling below them, and by painting them white.

(*c*) *Flat Roofs.*—Flat roofs are not now constructed for residential buildings in the Deccán, but are the rule in up-country areas in the dry and intensely hot province of Sind. There (Fig. 207) they are carried on rolled steel beams, each of which spans the width of the room at its centre, and across these are light tees, 2×2×¼ inch, laid flange downwards, supporting flat tiles 12×12×2 inches, on which are layers of mud plaster, 1 inch, 1 inch, and 2 inches (on top) thick, alternating with 2-inch layers of "bhán" (bran, chaff, etc.), and finished off on top by lime plaster 1 inch thick, giving a total thickness of 11 inches of roof-covering. The top of the roofing should

FIG. 207 FLAT ROOFS



have a slight slope of about ½ inch to the foot to shed any rain which may fall, and this is led off by roof gutters formed on top of the walls and shoots. Double roofs of reinforced concrete, with a good air space between the upper and lower surfaces, are now being introduced. These should form a sanitary, water-tight, and cool covering, and one requiring little, if any, repair. The air space should be ventilated to prevent the air getting unduly hot, which it would do if confined therein.

(*d*) *Ceilings.*—A ceiling is not required under the Belgaum pattern, as the flat tiles take its place. A wooden ceiling should be of teak to ensure its permanence, and the boards should be tongued and grooved, and ¾ inch thick (as thinner ones will warp and the tongues cannot properly be formed in them), and they should be fixed by screws, not wire nails. If placed on the underside of the purlins the roof will be cooler on account of the air space thus enclosed, but that space may allow dust to collect, and rats to breed undisturbed. If fixed on top of the rafters, the boards are more liable to rot from contact with the tiles when wet, but on the whole this is the best position for them.

The old pattern of ceiling cloth is now rarely adopted, as such ceilings are a source of expense in maintenance, are liable to be stained by animals, and, if laid as entire sheets, are likely to sag and be noisy when moved by the wind. To get rid of most of these defects the ceilings should be made of independent panels on frames screwed to the roof joists, etc., each of which can be adjusted and repaired separately as necessary.

Lath and plaster ceilings are not constructed in India because they would suffer by expansion and contraction due to the considerable diurnal variation of temperature. Plaster on wire netting would meet this difficulty, but would be expensive.

332. Verandahs.

Remarks as to the architectural treatment and height of verandahs have been made in Article 323 (*b*), and as to their width in Article 328 (viii). Although verandahs give protection from the weather, they are primarily required for shade in the tropics, and thus in the northern hemisphere are not wanted on the north side. On the east side they are not very necessary, as this gets only the morning sun, when the air is naturally cool. Instead of a verandah there, minor rooms which are occupied only for a short time can be placed to protect the inner rooms, and can themselves be shaded if desirable by projecting the eaves of the roof, say, to 3 feet from the wall. The south side is the hottest of all, as it gets the sun throughout the day, and in Sind faces the prevailing wind; it therefore requires a verandah there, but elsewhere minor rooms may be substituted for that and treated as just noted. The west side faces the afternoon sun, when the air is heated, and in the Deccán the prevailing wind; there it requires a verandah to protect it (Figs. 200–203, pp. 802*a* and 804).

Not only should the verandahs be reduced in number for economy as far as practicable, but also their width should be diminished where possible, and this will allow of increasing it where desirable for better accommodation. Thus the part of the west verandah of a residential bungalow, which is used only as a passage, might be reduced to 6 feet in width, while that opposite to the drawing-room might be widened to 12 feet, or, better, to 14 feet, to serve as an anteroom or sitting-out-place. Similarly, for an inspection bungalow the verandah at the entrance might be widened to 10 feet, or better to 12 feet. Such differences in width will also serve to give variation to the elevation of the building.

The verandah roofs of inspection bungalows and of small residential bungalows are often carried on posts and post-plates. Here trellis work in front will have some architectural effect as giving a bounding face to the building. It will look best and aid ventilation if not continued to the eaves, but formed as a strip 6 feet high between teak or jarrah frames 2 × 2 inches (of which the lower bar is 6 inches clear from the floor), and teak battens 1½ × ½ inch, crossing each other at angles of 45°, so as to enclose blank lozenges, 2 × 2 inches; thinner, narrower battens look weak and deteriorate quickly. In this screen should be trellised doors and windows opposite the similar apertures of the main building, so that the former may be opened to admit more air and light when necessary. Similar strips may also be fixed in verandahs of larger buildings with masonry or brick fronts to diminish the glare, while still allowing the shadowed recess behind to set off those fronts. In the rainy coastal districts the exposed west verandah may be enclosed by glazed shutters, but these are not advisable up-country, where the temperature is hotter (Art. 323, end of (*b*)).

333. Colour-washing Walls.

In the hot parts of India walls are not papered, but are colour-washed, which is really more architectural; there paper might harbour insects, and would probably fade quickly, and blister and peel with the heat. To get the best effect, manufactured distempers, and not crude, locally prepared colour-washes, should be used. If the latter are adopted, care should be taken to make them properly adherent by means of rice-water, gum, or glue and salt, so that they will not rub off nor come off on clothes, etc. For private residential buildings effect should as far as practicable be given to the wishes of the occupants in respect to the tints to be adopted, except when unusual colours are desired, and it is not likely their successors will approve of them. For public offices and residential buildings the colours should be unobtrusive.

The darker the room, the lighter should be the colour, so that the room may be well lit. Pure white, however, looks cheap and soon gets dirty, so that it should seldom be used for an interior, but it is the coolest colour for the exterior of a building. Bathrooms, servants' quarters, stables, etc., should be whitewashed for sanitary reasons. Light yellow or orange lights up best, and dark red worst. As a rule, colours should be put on in light washes, so that they may be even and not show brush marks; they should not, however, be so light as to appear white. The colouring should be quite flat and uniform. Glazed oil colours show up inequalities of the plaster and look cheap and vulgar.

White borders to corners of rooms and the exterior of buildings, and round door and window frames, seem to be with some a favourite form of ornamentation, but do not appear advisable for the following reasons:

They involve additional expense in labour;
They are apt to get dirty, and when dirty make the wall unsightly;
When clean they make the body of the wall look dirty and kill its colour;
They are too emphatic where emphasis is not required, and thus they destroy breadth;
The narrow width of the border has not any architectural strength nor structural meaning;

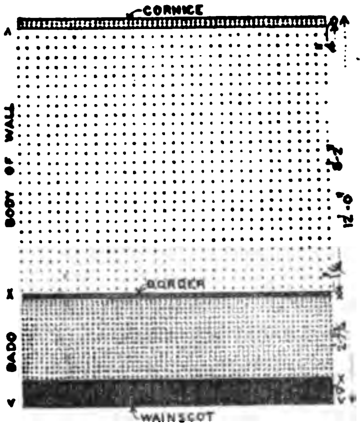
> There are no outlines in Nature—thin strips of white on the exterior edges of buildings demarcate them harshly from their surroundings.

When, however, a wall has architectural mouldings and features, such as footings, copings, door and window mouldings and pilasters, the whitewashing of them is not objectionable.

As a rule, painted dados are better suited for the rooms of public than of private residential buildings, but can be adopted for the walls of verandahs, staircases, and passages of the latter. Verandahs of public buildings need not be colour-washed, and their shaded recess will look all the better from the exterior if the masonry or brickwork is left plain. Dados involve the use of dark tints, and therefore should be painted with good distemper, not local colour-washes. Fig. 208 shows how a wall may be painted with three depths of the same colour; for private residential buildings coloured cornices and wainscots will look effective and unobtrusive. Dados are economical, as they alone need be re-coloured frequently; the upper part of the wall which is beyond ordinary damage may be coloured less often. They are also architectural, as they and the cornice correctly emphasise the base and the top of the wall, and differentiate them from its body.

FIG. 208

COLOURING WALLS



334. Doors.

Doors are an expensive item in a building, and should therefore be reduced in number, size, and quality as much as is practicable. In residential buildings it is better that, as in England, bedrooms do not communicate with the main day-rooms, or with each other, so that they may be more private and sound-proof, and wall space may not be cut up by the doors. In inspection bungalows, however, communication doors are generally inserted in the dividing walls; when there are such doors they should have wooden, not glazed, leaves, which destroy privacy. External doors may have their door heads open to secure ventilation, but the heads should be fitted with fine wire netting to keep out birds, bats, etc., or wire gauze to prevent the entry of mosquitoes, etc. If desired, glazed fanlights may be placed in them, and be similarly protected. In no case should door heads in partition walls be open so as to ventilate one separate room into another, but they may be inserted above rooms *en suite*.

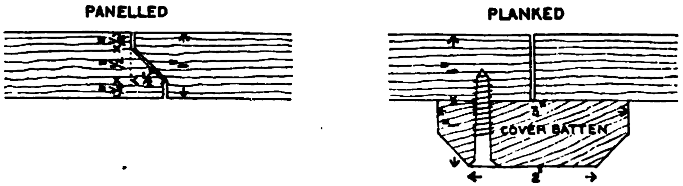
The following are good internal sizes and classes for doors:

	Feet.	
Main rooms, external	7½ × 4,	panelled and glazed in two leaves.
Bedrooms, external	7 × 3½,	panelled in two leaves.
Minor rooms, internal	6½ × 3,	plain planked in one or two leaves.
Bathrooms (sweeper)	5½ × 2½,	plain planked in one leaf.
Servants' quarters	6 × 2¾,	plain planked in one leaf.

For bungalows all door-frames should be of teak; the leaves of external doors may be of teak, but those of internal doors should be of jarrah for the sake of economy. For outhouses cheap local wood may be used. In India the sills of door-frames are exposed above floor level, presumably with the idea of excluding dust; in England they are omitted or concealed below the floors, and there seems to be no good reason why the practice there should not be followed in the East. The vertical meeting joint of panelled door and window leaves should be rebated or made to overlap, as shown in Fig. 209, and planked leaves should have a cover batten; the actual meeting joint may thus be eased a little to prevent jamming due to expansion, and the proposed treatment will obviate an opening when contraction takes place.

FIG. 209

MEETING JOINTS OF SHUTTERS


PANELLED

PLANKED

335. Windows.

Windows are another expensive item in a building, and should similarly be reduced in number, size, and quality as much as is practicable. They are formed cheaply of leaves opening outwards, and not as expensive sashes with counterweights, the cords of which might not last well, and the recesses for which might harbour insects, etc. Window heads may be left open for ventilation, and fitted with netting or wire gauze, as in the case of door heads.

The following are good internal sizes and classes for windows :

	H. Ft.		B. Ft.		Height of Sill above Floor. Ft.	In.
Main rooms	4½	×	3½,	two leaves	2	6
Bedrooms	4	×	3,	two leaves	3	6
Dressing-rooms	3½	×	2½,	two leaves	4	0
Bathrooms	1½	×	1½,	one leaf	5	0
Servants' quarters	2	×	2,	one leaf, planked ..	4	0

Bedroom windows on the ground floor can with advantage to privacy be divided by horizontal framing into two parts, the upper smaller leaves of which can be opened independently of the lower ones.

For bungalows all frames should be of teak, and for economy all leaves of jarrah ; for outhouses cheap wood may be used. Window-sills should be of wood, 1 inch thick, so that articles may be placed on them without getting dirty. They should be level, so that articles can stand on them, and should not slope to the window for the drainage off of rain-water, which is very rarely required. They should project internally from ½ to 1 inch to protect the edge of the plaster below them. Bedroom windows of residential bungalows, and all windows of inspection bungalows, should have frames filled with ½-inch galvanised iron netting, so that the windows may be kept open at night without cats, bats, etc., entering through them.

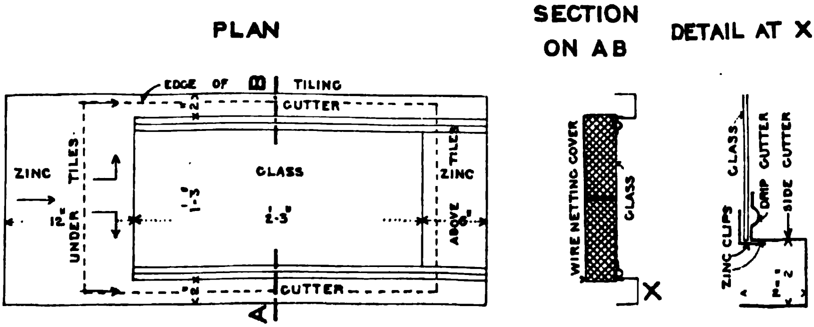
Frosted glass panes should be fitted into the lower halves of windows of day-rooms, as a protection from glare, into the lower half or two-thirds of those of bed- and dressing-rooms, and into the whole of bathroom windows, so as in addition to secure privacy. Panes painted with flatted oil paint do not look so well and are less translucent ; moreover, the paint generally gets scratched and thus becomes useless for its object of securing privacy. All putty joints should be neatly struck, and the frames should be oiled before the putty is put on so that it may adhere properly to them.

Clerestory windows are hardly necessary in the Deccán for residential and inspection bungalows; the ropes to actuate them are unsightly, and the windows are generally dirty, as they cannot easily be cleaned. To provide for them the walls have to be unnecessarily high for small rooms. If the clerestory openings are of small height, and are protected from the ingress of rain, either by the projecting roof eaves, or by special weather boards, they need not be fitted with glazed shutters. It will suffice to have fine wire gauze shutters, which will prevent glare and exclude dust and mosquitoes.

Skylights are required only when there is not any, or insufficient, external means of lighting a room, as they tend to cause heating. They should always be raised above the plane of the roof, and should have zinc flashing all round them; even then, when the frames are of wood, skylights usually leak, owing to the expansion and contraction of the wood. A better form, where the framing is wholly metallic, is shown in Fig. 210.

FIG. 210

SKYLIGHT



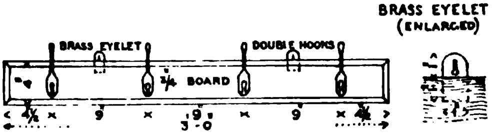
336. Fixtures and Fastenings.

Much of the comfort of the occupants of a building depends upon the due provision of fixtures and fastenings, and the proper maintenance of the latter. The positions of (i) and (ii) below should be arranged on plan, so that they will not interfere with those of doors, windows, main articles of furniture, etc.

(i) *Wall Shelves and Cupboards.*—In all bedrooms and dressing-rooms recesses should be built (in inner walls)—say, 5 feet high and 3 feet wide—with their sills (to be of wood) 2 feet above floor level; the shelves should be 1 inch thick, and at least 10 inches wide and 12 inches apart clear. In private residential buildings and in the main rooms of inspection bungalows these shelved recesses should preferably have locked leaves to form them into cupboards, with their base, say, 9 inches above floor level; these should not project more than 2 inches from the face of the walls.

(ii) *Peg Boards.*—In all bedrooms and dressing-rooms and in the main rooms of inspection bungalows there should be in each at least two sets of peg boards, say, 3 feet long, 4 inches wide, and ¾ inch thick, with chamfered edges, and with their centres fixed 5 feet 9 inches above floor level. The hooks

FIG. 211 PEG BOARD



should be four in number, 9 inches apart centres, and should be of solid iron or brass, each with two knobs or swelled ends, and not with china or screwed tops, which soon come off. At the back of the board should be fixed two brass eyelet holes, so that the board may be lifted off the supporting nails when the walls have to be colour-washed (Fig. 211).

(iii) *Bathroom Shelves.*—It will be a convenience to have fixed to one of the side walls and 2 feet above the floor a shelf 2 feet 6 inches long, 7 inches wide, and ¾ inch thick, with a ¼-inch ledge projecting all round it. The shelf should be pierced with a few small holes for drainage, and should be supported by thin wrought-iron strut brackets and hangers. A small corner quadrant shelf for the chamber is also convenient.

(iv) *Dispense* (*Pantry*) *and Godown* (*Storeroom*).—Shelves should be provided along the whole length of the rooms—12 to 18 inches wide and 12 to 15 inches apart. The bottom one should be 18 inches above floor level, and there should be three others above it. In residential bungalows as much shelving as possible should be provided. The shelves may be of cheap wood, they should be well supported by wooden strut brackets, and they should have edge ledges.

(v) *Picture Rails.*—Provision for these should be made in residential bungalows in rooms in which pictures will be hung, to obviate the necessity for driving nails into their walls.

(vi) *Verandahs.*—Good shelves of cheap wood can with advantage be provided in the back verandahs of all bungalows. In the front verandah of an inspection bungalow it is convenient to have a 4 feet by 2 feet flap table, which can be let down parallel to the wall when out of use, and can be supported by a hinged bracket when in use (Figs. 202 and 203, p. 804). A lamp bracket may be fixed to the wall above it.

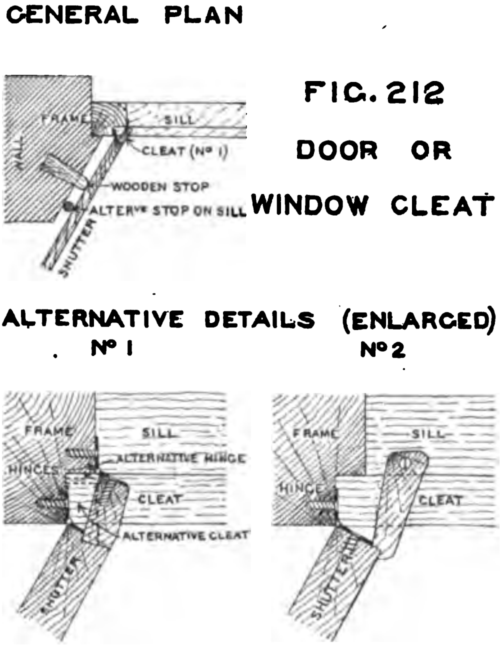

GENERAL PLAN

FIG. 212

DOOR OR WINDOW CLEAT

ALTERNATIVE DETAILS (ENLARGED)

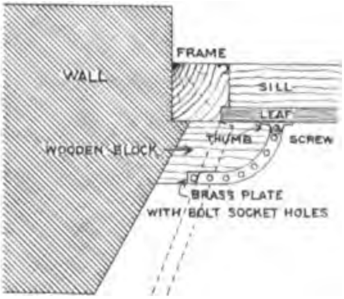
No 1 No 2

(vii) *Lamp Brackets.*—These should be fixed over the dressing-table in each dressing-room, and at one corner of each bedroom and bathroom.

(viii) *Door and Window Cleats.*—Good forms of these, which are fixed about half-way up the leaf, are sketched in No. 1 of Fig. 212. Of these the cleat shown by dotted lines, which abuts end on against the frame, and thereby receives support from it when the shutter is open, is superior to that shown by full lines, which is not thus supported. The usual form of sill cleat (No. 2) is inconvenient, being difficult to manipulate. Hooks are objectionable, as their shanks are apt to get bent, the hook to become opened out or closed in, and the whole to squeak when wind moves the leaf to which they are attached. They also injure the walls and the floor or window-sill.

FIG. 213

DOOR OR WINDOW ADJUSTER

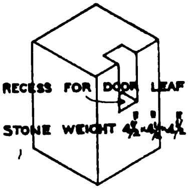


(ix) *Door and Window Adjusters.*—It is desirable to keep doors and windows only partly open when a strong wind is blowing, in order to deflect that from the occupants of the rooms. This can be arranged for as shown in Fig. 213 by a quadrantal sill block with a brass strip, in which holes are bored to take a thumbscrew fixed at the bottom of the leaf of the window or door. If preferred, a stouter quadrantal brass strip can be fixed, projecting from the top lintel instead of from the sill.

(x) *Door Weights.*—With the same object in view, stone door weights to clip the door leaf and hold it any desired angle can be provided for inspection bungalows (Fig. 214), or can be made as light iron standards with a lifting handle. These are, however, apt to injure the leaf and to get in the way, and are thus not so good as (ix) above.

FIG. 214

DOOR WEIGHT



(xi) *Door and Window Stops.*—To prevent the leaves of doors and windows from injuring the plaster of the reveals, wooden stops, say, 1½ inches in diameter and projecting 1¼ inches from the walls should be fixed opposite half-way up the leaves, or, better still, can be placed on the sills near the outer edge of the wall (Fig. 212).

(xii) *Bolts.*—Doors and windows should bolt from the inside; when the doors are in walls separating two rooms, the more private of these should be taken into account in this respect. When doors and windows are in two leaves, the first closed leaf should have bolts at top and bottom on the inside, and the other leaf only one at top on each side. For doors, if the latter has a bottom bolt, that may automatically drop and prevent the door from being opened from the outside. Single-leaf doors should be hung so that when partly open they will disclose as little of the rooms as possible.

(xiii) *Door and Window Furniture.*—Bolts, locks, and hinges of doors and windows of main rooms should be of brass fixed by brass screws. Those of minor rooms, especially in inspection bungalows, may be of iron, which should be kept well japanned.

(xiv) *Sunshades or Weather Boards.*—These should be fixed outside doors and windows in walls exposed to the sun and rain. It will be advisable to make their angle of slope adjustable to suit the varying amount of light in different seasons.

(xv) *Notice Boards.*—In inspection bungalows should be the following notices in neat glazed frames suspended by good cord from brass-headed nails:

Conditions of occupancy;
List of furniture;
Miscellaneous.

The last named should give the times of arrival and departure of the post, the names and distances of the nearest post and telegraph offices and railway stations, and other information useful to a traveller. The furniture list should be kept up to date, and the condition of the articles noted in it.

(xvi) *Furniture.*—A large part of the utility of an inspection bungalow is lost if it is not simply furnished for at least the requirements of a single officer, so that at any time, when necessary, he can make rapid inspections lightly equipped. The furniture should be plain and substantial, without being clumsy, and is best prepared at headquarters, so that its manufacture can be supervised and passed before it is sent out to the bungalow.

337. Maintenance and Repairs.

(i) *General Remarks.*—The annual cost of a building depends upon—

The interest on its capital cost;
The depreciation allowed on that cost;
Maintenance and repairs.

The interest is a fixed percentage charge on the capital expenditure, the amount of which should therefore be reduced as much as possible by careful planning and sound but simple construction. Inferior work may prove dear eventually, may be insanitary, and may affect prejudicially the comfort of the occupants, who deserve consideration, as under rules they have no option but to occupy the buildings provided for their accommodation. Moreover, the State for its own credit should not erect indifferent structures.

The depreciation is also a fixed percentage charge on the capital cost, but its rate should vary with the nature of the construction, being least when that is of the most durable character.

Maintenance and repairs are generally limited to a percentage amount of the capital cost, but should be reducible by proper economy, so as to avoid unnecessary work and expenditure.

The amounts of the first two items depend greatly on how the building was erected, and after its completion are not usually susceptible of alteration ; it is only the third item with which those responsible for its upkeep can deal. If maintenance charges are reduced to the minimum, the capital cost can be increased proportionately, and thus more accommodation (which is generally desired) can be secured without adding to the annual cost to the State or to the tenant.

(ii) *Execution of Repairs.*—Repairs should usually be started as soon as possible after the close of the rainy season, during which most of the damage will have been sustained, and they should be completed as soon as practicable, so that the building may be in good order for the greatest length of time. When an occupied building has to be attended to it is essential that the occupant should be put to as little inconvenience and for as short a time as may be. Before any work is commenced care should be taken to have all materials required on the spot, or their prompt delivery absolutely arranged for. Ample notice should be given to the occupant when it is proposed to commence and when it is hoped to complete the work, and the order in which it is carried out should be, as far as practicable, in accordance with his wishes.

(iii) *Tile Turning.*—This should be done as little as possible, and only defective, leaky parts of the roof attended to, as the work in connection with the turning tends to break old tiles, which are much more water-tight than the new ones which replace them. An iron rod ½ to ⅜ inch diameter fixed along, and just above, the eaves board will prevent tiles from slipping.

(iv) *Colour-Washing.*—Much money is frittered away on this item. When properly done it should last at least three years, and it would be as well in the case of private residential buildings to have fixed a time limit for colour-washing at State expense. For buildings rarely occupied work should be deferred until it really becomes necessary, and repairs should be restricted chiefly to dados (Art. 333). Care should be taken at once to remove all splashes on woodwork, etc., caused during colouring, by rubbing them off first by a wet and then by a dry cloth; it is better to avoid them by temporarily covering up the parts thus likely to be discoloured. Too many coats of colour wash should not be placed on each other, as then all are likely to flake off. Walls should be scraped and cleaned before a new coat is applied to them, particularly the mouldings, which would otherwise get their sharpness and form obliterated by repeated coats. Good brushes should be used.

(v) *Doors and Windows.*—The woodwork of these should be preserved, especially just before the rainy season, by applying linseed oil to them as sparingly as possible, so that it may not run and form drops and lines which will remain sticky for a long time; if the oiling is well done, it should not be necessary to renew it annually. Thick and blistered old coats should be scraped off before a new coat is applied.

The leaves should be made to fit, and should continually be kept in adjustment, and with all fittings in repair. Much of the comfort of the occupants depends upon this.

(vi) *Inspection Bungalows.*—The caretaker should—

Keep the building, outhouses, etc., clean;
Tidy up the grounds and attend to plantation work;
Whitewash the cook-room, stable, etc., when required;
Keep all windows clean (clear sheet glass obstructs about 20 per cent. of the light, and dirty glass, of course, much more);
Keep the furniture clean.

The furniture should be maintained in good repair, for which purpose a carpenter should be sent along the road or canal concerned so as to attend to all the buildings one after the other. It should be dull polished occasionally by the care taker, using a furniture polish consisting of—

¼ pint turpentine,
¼ pint spirits of wine,
¼ pint vinegar,
⅓ pint boiled linseed oil,

which should be well mixed and shaken just before use. The furniture should first be dusted and cleaned, and all grease spots removed by flannel dipped in a warm solution of washing soda. Then a little of the polish should be applied by means of a clean, soft piece of flannel, and thereafter the article should at once be polished with a very soft duster.

The buildings should be inspected as frequently as possible by the superior staff in order to see that they are properly maintained and are kept clean.

ADDENDUM.

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ADDENDUM.

1. *Actinic Rays* (*p.* 1).—The Department of Agriculture, U.S.A., has recently discovered that plant life depends for development much more upon light than on temperature. This fact is, however, disguised since light and heat generally accompany each other. At one time plants may require rest, but at another, stimulation; thus during times of prolonged and intense light they benefit by being darkened, while in ones of insufficient natural light, by the application of artificial illumination: even moonlight after dark days has been known to accelerate growth. Popular opinion, however, erroneously credits the presence or absence of heat as the determining factor of plant vitality.

2. *Capital and Maintenance Cost of Irrigation in India* (*p.* 2).—The average capital expenditure on Major Works for the whole of India is Rs. 33⅓ per acre and varies from Rs. 18½ in Sind to Rs. 86 per acre in Bengal: the fluctuation in different provinces is due principally to variation in rainfall but also to other physical conditions and the nature of the works. The general average cost of maintenance is Re. 1 per irrigated acre and varies from Re. 0·4 in Sind to Rs. 2·5 in Bombay: the provincial differences are chiefly caused by the extent and degree of concentration of the irrigated areas.

3. *Hydrographic Boundaries* (*p.* 6).—In some notable instances—the Periyar in Madras and the Upper Chenab in the Punjab—Indian engineers have had to neglect hydrographic boundaries when obtaining supply for their works by leading that from one hydrographic district where it is running to waste into another where it can be utilised. Even in such cases it is generally advisable to confine the actual irrigation to a single hydrographic district.

4. *Seepage* (*p.* 20).—The fair weather flow of streams results practically from seepage from their catchments. Natural seep-

age is likely to remain constant so far as the soil is concerned (as that is in a settled condition in respect to porosity), and to vary directly as the saturation by rainfall. Artificial seepage, due to the irrigation of previously dry land, will at first probably decrease slowly per unit of area, as the subsoils get choked by infiltering matters and become consolidated by the superincumbent pressure acting with increased effect on the newly moistened strata, but such decrease may be more than balanced by the effect due to the growth of irrigation.

Not only must the amount of seepage be taken into account, but also the time when it passes into the stream: what issues during high-water stages is of little use except for storage schemes, but what arrives at low-water ones is of great benefit to all classes of irrigation works as it increases their supply when more water is most needed. The extra fair weather discharge produced by seepage from irrigation should be ascertained by gauging for some years before construction is proposed to utilise it.

5. *Drainage* (*p.* 22).—The first consideration should be paid to seeing that the outfall of the drainage system is clear and unobstructed (p. 247), for, should it be blocked, all the drains upstream will be rendered partially, or wholly, ineffective. The rear drainage of dams (p. 166) may be interfered with by the detritus carried down the waste weir tail channel. It is best to avoid this by arranging to have the outfall of such a channel well below that of the drains: where, however, this is not practicable, the free flow of the drainage water must be maintained by excavation through the blocking débris, or by passing it in a slab drain under that.

6. *Loss by Evaporation* (*p.* 24).—It is said that from 50 to 75 per cent. of the discharge from the great equatorial lakes of Central Africa is lost by evaporation in the "Sudd" district of the Nile. There the river spreads out from 10 to 30 miles wide and is choked and retarded by the floating sudd weed and its margin is fringed by aquatic growth, all of which aid in causing the loss. It is proposed to diminish the evaporation by narrowing the river channel by means of embankments which should reduce all the above factors of loss.

7. *Number of Waterings* (*p.* 40).—Experiments[1] on wheat growing near Quetta, Baluchistan, India, show that it is advantageous there to reduce the number of waterings from seven to one and that the increase of the crop varies directly as the waterings are diminished as noted in the table below—

	30 acre inches spread over				
	1 acre.	2 acres.	3 acres.	4 acres.	6 acres.
Grain—bushels ..	47·51	91·42	130·59	166·16	226·16
Straw—pounds ..	4,532	2,908	10,256	13,204	17,916

The following five principles are enunciated in the bulletin—

1. The irrigation water available should be spread over the largest possible area.
2. Heavy waterings reduce the proportion of grain to total crop.
3. The growth period of wheat is increased by heavy watering.
4. When the water supply is limited, the root development of the wheat crop must be deep.
5. The soil moisture must be preserved as far as possible by a surface mulch of dry soil.

The reduction of the number of waterings not only increases the yield per acre irrigated, but also makes possible a large extension of irrigation. Heavy waterings increase the proportion of the less valuable straw to the more valuable grain. The longer the crop is in maturing the greater are the agricultural risks run, and if growth is continued to the hot weather, the grain will not be properly filled. Roots should be encouraged to grow rapidly when the plants are first started, and for this reason the soil should be well cultivated and aerated. Excessive watering causes the ground to cake and become hard and deprives it of aeration; thus the roots tend to keep near the surface, and not to penetrate deeply and depend upon subsoil moisture for their growth. The soil moisture should be utilised in developing the plant and should not be wasted in evaporation: this is effected by preserving a good tilth in the early stages of growth; during the later ones it is not so easy to maintain that.

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[1] Fruit Experiment Station, Quetta, Bulletin No. 4, "The Saving of Irrigation Water in Wheat Growing," by A. Howard, C.I.E., M.A., and G. L. C. Howard, M.A. Baptist Mission Press, Calcutta, 1915.

Although the principles noted are sound, and every effort should be made to follow them, it is not likely that in practice the conservative cultivator will at first greatly reduce his expenditure of water: his education will take time and require guidance; the revenue prospects of projects must be forecasted accordingly.

8. *Mortar* (*p.* 77).—Fat, or calcined pure lime will not set in the heart of a thick wall, where it cannot get the carbonic acid required to enable it again to become a carbonate, and thus solidify and harden, but will remain pulverulent without cementing effect. The calcined constituents of hydraulic lime will, however, recombine and set of themselves when moistened. Its setting will be accelerated and its hardening increased if it is "gauged" (mixed) with, say, one-sixth its bulk of cement; such gauged mortar may be required where the masonry will early be subjected to water infiltration or erosion. The surface of mortar joints is rendered hard and dense by rubbing them with a special trowel as soon as they have begun to set.

On certain works where the ordinary sand contains soft grains, it has been found advisable to substitute for it rock crushed to ½ inch gauge. If this material is used in its original clean state, it is unnecessary to screen out its dust as this is as hard as the larger particles—in fact, variations in the size of the aggregate of the mortar are beneficial by enabling that to fill voids in the masonry more completely (compare the "effective size" of sand, p. 432).

Thorough grinding of mortar greatly improves its quality and increases its hardness when set by ensuring the perfect amalgamation of its constituents.

9. *Needles and Horizontal Planks* (*p.* 85).—Needles under low heads have the further advantages that they can be worked by one man, admit of rapid removal, require fewer piers and do not have lifting hooks which may be broken.

Horizontal planks have to be worked by at least two men; they are liable to jam, and if this occurs with a low one and that is not horizontal, trouble is occasioned; and the water falling over them pounds the floor downstream; they, however, obstruct floating rubbish less than do needles. By means of double planks and earth filling between them leakage can be stopped (Fig. 66, p. 287).

10. *Abnormal High-Flood Discharge* (*p.* 105).—Instances of this have occurred at the Nadrai Aqueduct[1] across the Kali Nadi on the Lower Ganges Canal, 33 miles below the head-works at Narora, which had originally five spans of 35 feet on wells 25 feet deep. When the work was designed the high-flood discharge was estimated at 9½ cusecs per square mile of catchment (2,377 square miles, having an average rainfall during nearly 30 years of 32 inches a year), or 23,000 cusecs. The canal was opened in 1878 and on the 4th October, 1884, came a flood of from 40,000 to 50,000 cusecs which led to proposals for the construction of another aqueduct having nine spans of 35 feet: this, however, was not constructed and the old one was patched up. On the 17th July, 1885, occurred a flood of 135,000 cusecs which swept the old work away and did extensive damage elsewhere. This flood was carefully observed by the engineers in charge who found that the rainfall on 1,000 square miles of the catchment was 20 inches, which fell in about 24 hours, and that the run-off effect was increased by improved drainage arrangements. The new Nadrai Aqueduct, since constructed, has fifteen spans of 60 feet and a waterway of 23,325 square feet, which, with an assumed mean velocity of 6 feet per second, gives a discharging capacity of 140,000 cusecs. The highest flood from 1885 to 1902 was only 15,000 cusecs.

As the 1885 flood was of such abnormal intensity, it may seem hypercritical to suggest that the discharging capacity provided, which was only slightly in excess thereof, may still prove somewhat insufficient. As, however, that flood was due to extremely heavy rainfall on less than half the catchment, a still larger one is possible: the work will, doubtless, be able to discharge it with a small amount of heading up.

Meteorology is the most inexact and difficult of all sciences, and hitherto it has not been found possible to predict its effects infallibly.

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[1] "Notes on Irrigation Works" (pp. 28–30). by N. F. Mackenzie. Constable & Co., 1910.

11. *Estimates* (*p.* 131).—The remarks made apply to departmental detailed estimates and not to commercial lump sum ones. The former are estimates, pure and simple, of the probable cost of construction under normal conditions. The latter are really tenders, and the contractor, to guard himself against loss, has to allow liberally for all possible contingencies. When a work is to be carried out by contract it is therefore better to have the tenders based on a schedule of rates including those for extras.

12. *Headers for Masonry Bond* (*pp.* 153 *and* 262).—It has been objected that headers are unnecessary for uniting battering facework to the hearting of masonry walls, as the batter itself gives cross bond, and are harmful in that they lessen the longitudinal bond. It is generally considered, however, that it is desirable to have them so as to resist any tendency to separation, and that as they are placed at intervals, they cannot much affect the longitudinal bond, which can and should be ensured by building in other headers placed longitudinally in the heart of the wall.

13. *Progressive Excavation of Canal* (*p.* 229).—The suggestion that it may be advisable at first to excavate a reduced section and thereafter to increase it when necessary, so as to keep in advance of the requirements of an extension of irrigation, applies particularly to long and deep cuttings in soft rock, etc., which will disintegrate by exposure to the weather, and will thus be rendered easier and cheaper to remove after such disintegration has taken place.

14. *Distance Marks on Canal* (*p.* 248).—Where stones are not available, or may be attacked by subsoil salts, iron marks are fixed. In Sind these are formed by vertical angle irons about $2\frac{1}{2} \times 2\frac{1}{2} \times \frac{1}{4}$ inches and $2\frac{1}{2}$ feet long, embedded $1\frac{1}{2}$ feet in the ground, and each has fixed at top a horizontal wrought iron plate about $6 \times 3 \times \frac{1}{8}$ inches on which the mileage is painted. In the Punjab iron slabs are embedded 1 foot into and projecting 8 inches above brickwork blocks 2 feet in diameter and $1\frac{1}{2}$ feet deep with their tops rounded above ground level to shed the rain.

15. *Batters of Weirs* (*p.* 260).—Water passes over a weir in a parabolic path. The point where the overfall will strike

the battering face of the weir depends upon the onward horizontal mean velocity of the water, x (due to its head h, and allowing for retardation by all causes), and its downward vertical acceleration, y (due to the action of gravity). In any time, t, the amounts of these are—

$$x=\tfrac{2}{3}\sqrt{2gh}\,t \qquad y=\tfrac{1}{2}gt^2$$

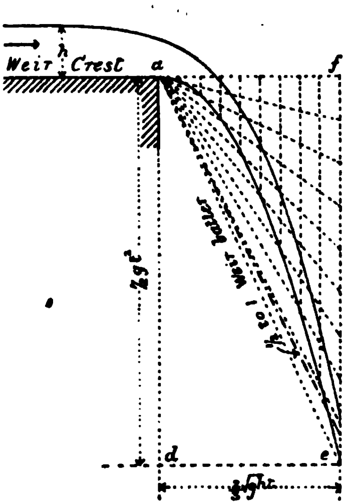
and therefore—

$$y=\frac{9}{16}\cdot\frac{x^2}{h}$$

In Fig. 215[1] $af=\frac{2}{3}\sqrt{gh}\,t$ and $fe=\frac{1}{2}gt^2$ are divided into the same number of equal parts and the parabola is drawn through the intersections of verticals from the divisions of af with the sloping lines from a, the downstream edge of the crest of the weir, to the divisions of fe.

FIG. 215

WEIR OVERFALL



As the discharge over the weir increases, so also do the depth at which the batter is struck by the overfall and the momentum of the striking water. Thus the whole slope above tail water level will be subject to impact, the lower parts severely for a comparatively short time and the upper ones more and more gently for longer times: the former will thus require greater protection than the latter. Such protection can be given by—

Raising the level of the surface of the water cushion downstream;
Projecting the crest of the weir downstream (Fig. 54, p. 261); or by
Paying attention to the face joints of the masonry slope.

Wide joints are liable to be blown out by the concussion of the overfall and therefore the face joints should not exceed one-half inch in thickness. The joints will generally suffice if laid in hydraulic mortar well rubbed on the surface, but may be made harder by using gauged mortar (6 of lime to 1 of cement), or, in extreme cases, neat portland cement mortar.

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[1] Encyclopædia Britannica, 11th edn., Vol. XIV, Article "Hydraulics," p. 51.

The width to be allowed for the water cushion of a weir can be ascertained from the above Figure and equation, but extra provision for it will have to be made to enable the volume of the water contained in the cushion to steady the onward rush due to the overfall. (See also Art. 32 (*b*), p. 54.)

16. *Tree Belts for River Training* (*p.* 351).—Although trees by themselves will not resist undermining by a river ((viii) on p. 328 and (vi) on p. 373), it has been proposed to form tree belts of from four to 12 rows of trees along existing canal banks and river embankments, each line of which when threatened by erosion would be chained to the row inland of it so as to secure anchorage. This system has not been tried on a scale large enough to test it, and the belts to be effective would have to be established many years before they would come into action.

17. *Concrete Piles for Hurdle Dykes* (*p.* 355).—The proposal to use concrete piles has recently been carried out on the Missouri River: there the piles have fastened between them wire cables to which are attached upstream screens of trees and brush, or A frames faced with wire netting.

> "In sinking the concrete piles a water-jet pile is employed. The latter is from 20 feet to 40 feet long and 16 inches or 14 inches square. A 4-inch pipe extends through the centre nearly to the point, and has ½-inch lateral branches, spaced 30 inches on centres, which end in elbows turning upward along the sides of the pipe. A 2-inch pipe having a separate hose connexion extends through to the point. In some cases this pipe is omitted and the 4-inch pipe extends to the point where it terminates in a 2-inch nozzle. Thus, in addition to the boring jet, there are streams of water flowing upward along the sides of the pile."—*The Times Engineering Supplement*, June, 1920, p. 205.

18. *Objections to River Embankments* (*p.* 372).—A further objection made to river embankments is that, by causing the

riverain area to rise more rapidly by increased silting, they still further heighten the high-flood level beyond what they do by confining the river floods within that area. As the protected country inland remains at its original level, it will therefore slowly become lower and lower with respect to the altered high-flood level, and the embankments will thus be rendered more liable to breach and the damage resulting from a breach will be intensified. However, the silting up of the land upstream will prevent the raised bank from increasing in height on that side beyond its original one above ground level. Further, as the new earthwork will be added to the upstream slope and will be supported by the well-consolidated old bank (Art. 198 (*g*), p. 396), it will not be subjected to excessive water pressure. The rate of rise of the riverain area will, moreover, be so slow (Art. 192 (*b*), p. 372), that ample time will be obtained to observe the effect of the raising of the embankment to keep pace with it, and, if necessary, to devise measures to guard against undue danger.

In both respects—raising the riverain area by silting, and increasing the high-flood level by this and by confinement—a retired embankment (Art. 193 (*b*), p. 377) will be less prejudicial than one constructed near the river, while the first result of silting (which will take place at its upstream toe), will be to render it more stable by decreasing its virtual height.

19. *Alluvial River Control* (*p.* 377).—Fig. 216 illustrates very roughly the proposal to utilise retired embankments in a general system of river control. These embankments would be retired beyond the limits of all probable erosion (middle of p. 315); they would be aligned on the best and highest ground available, and not necessarily parallel to the course of the contemplated "future river." From them would start at intervals "reclamation bunds" (p. 346), A′A″ . . . Z′Z″, to afford them the protection of a still-water area (middle of p. 345), and to induce silting along them so as to create continuous "foreshores." These bunds would gradually be lengthened and strengthened to form "cross banks," A′A″A‴ . . . Z′Z″Z‴, the ends of which would finally be on a general sinuous alignment to give the river greater tortuosity (bottom of p. 345), whereby its longitudinal slope, velocity and erosive power would all be reduced. They would be finished off with "Denehy's groynes" (p. 350) so as to hold the river.

This proposal of course involves very heavy expenditure, but that need only gradually be incurred, and thus being spread over many years, might not be greatly in excess of the cost of maintaining the existing system of near embankments which are liable to erosion and often have to be replaced (top of p. 376). Moreover, it would not be necessary to apply it at once to the whole river as it could be started for a length having "inerodible abutments," upstream and downstream, such as occur on the Indus in Sind at the rocky ridge above Sukkur and the hard barrier at Kotri, at both of which places large railway bridges have already been constructed. Where a weir is contemplated that and its flank works would form a downstream abutment and the latter could be constructed in advance as part of the general system of control. Inerodible abutments, especially upstream, are essentially required to

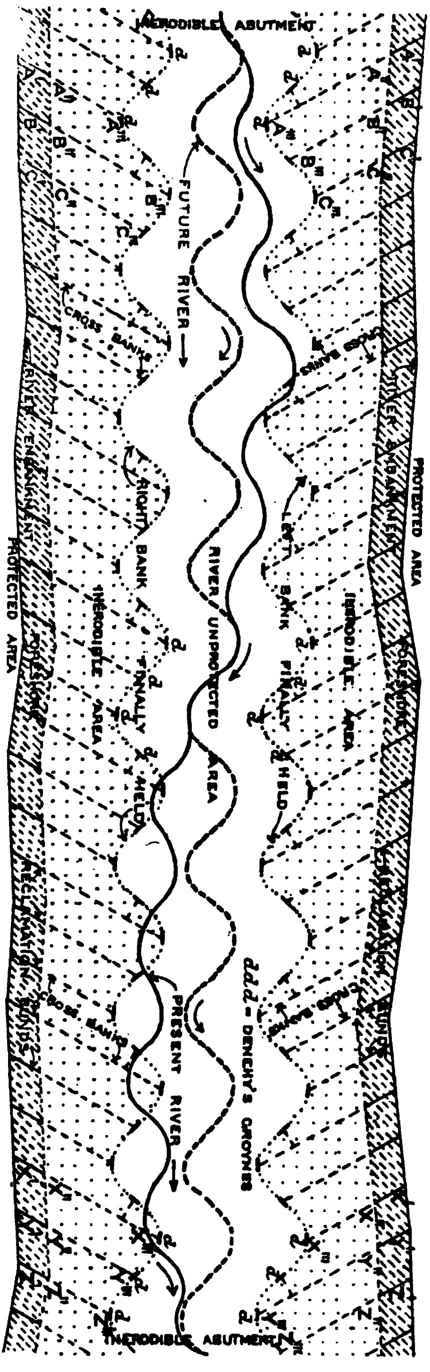

FIG. 216

DIAGRAM OF ALLUVIAL RIVER CONTROL

give permanent security to the whole system (middle of p. 348). The existing near river embankment would be maintained until threatened by erosion and would then be replaced by a length of the retired embankment.

It will be noticed that on the right hand of Fig. 216 some of the cross banks and the area protected by them intrude on the course of the "present river." Such reclamation would naturally not be undertaken until the river in its oscillations had abandoned the area. In fact, throughout the progress of construction advantage would have to be taken of the vagaries of the river, by extending the banks as the river receded, and thus to hold permanently the area to be reclaimed (middle of p. 357). Further, the various cross banks would have to be aligned and spaced so as to make the best of natural conditions.

The cross banks would be set out so as to avoid the formation of pockets (p. 380), and as far as practicable, symmetrically to each other (bottom of p. 355). On each bank they would be terminated so as to leave a wide area unprotected, thus giving the river considerable latitude to adjust its course in accordance with local conditions of gradients and soils.

Inland of the retired river embankments the country would be rendered secure for permanent conditions of agriculture and settlement. The area between these embankments would ensure for the river all the advantages enumerated on p. 376. The foreshore would improve the stability of the embankments, and on it and the "inerodible area" post-inundation crops, or forests, could be grown under permanent conditions but would be liable to inundation. It would be only in the "river unprotected area" that the existing insecurity of riparian land would be continued, but as experience of the behaviour of the river under control is gained, it should be possible greatly to reduce the extent of this area which would initially be made wide to give the river ample latitude to adjust its course to its altered regime. It is this last area which differentiates the proposal from practice in America where the river banks are themselves held, but at greatly increased cost for maintenance, which, however, is justified by the higher value of riparian land there. On the other hand, the plan of control sketched has the advantage that, when established, its maintenance should be comparatively cheap as only permanent material is employed in its construction.

The system of retired embankments may be novel but the other parts of the proposal—reclamation bunds, cross banks and Denehy's groynes—are not, and their efficiency has been established elsewhere. There thus seems every probability of the success of the system. Its cost will be high but may be amply justified by the results secured, whereby the river would be held to a permanent course and a large area of land would be protected from its present incursions, which prevent the attainment of the security of tenure that is so desirable for irrigation operations.

20. *Hydraulic Gradient of Alluvial Weir* (*p.* 436).—A curtain wall (p. 444) is most effective in reducing upward pressure downstream of it when placed upstream of the floor of a weir. The hydraulic gradient at it drops so that head may be gained to overcome the obstruction to flow caused by it: the more upstream the drop occurs, the greater is the length downstream which benefits from the consequent reduction of upstream pressure. If a curtain wall is placed downstream of a weir (p. 448) it is a precaution against retrogression and undermining. The upstream apron flattens the gradient and reduces pressures downstream: the downstream apron also flattens the gradient but increases pressures upstream.

It is of course essential that the upstream puddle apron (p. 443) should be in watertight connection with the masonry crest wall, for, otherwise, the hydraulic gradient will start from the separation line between them. The upstream apron is subject to a lifting force equal to the weight of the water below the hydraulic gradient, and is kept down by that below the high-flood line which is always somewhat greater of the two.

Fig. 106 on p. 436 does not properly compare the effect on the hydraulic gradient of the two aprons, for were the upstream apron omitted, the downstream one should correspondingly be lengthened. Then the gradients in the two cases would be parallel to each other and would show that an equal relief of pressure throughout the length of the longer downstream apron resulted from the construction of the upstream apron.

21. *General Remarks on Alluvial Weirs* (*p.* 439).—In the Punjab the general practice is to place the sill of the undersluices at canal bed level and to make the head regulator sill 3 feet higher and the crest of the weir 6 to 9 feet higher still,

while the top of the weir shutters is from 1 to 2½ feet above canal full-supply level. When there are falling shutters the width of the under sluices may be one-twelfth the length of the weir; and one-eighth when there are not. The spans of the undersluices may vary from 20 to 25 feet. The high-flood depth on the weir crest may be as much as 15 feet and the high-flood velocity 14 to 15 feet per second.

22. *Narora Weir Failure* (*p.* 447).—This large work was constructed in 1877, and falling shutters giving 13 feet head above the floor were added in 1882: it failed in 1898 when the head was only 12 feet. It is considered by some that the cause of the disaster was "piping" (p. 438), whereby the foundations were undermined and thus settled from the ashlar flooring, leaving that only 1 foot thick to resist the upward pressure of the water.

23. *Double Heads to Inundation Canals* (*p.* 465).—In some cases the heads are arranged to be worked consecutively: the main head is designed to give a good supply early for sowing, and the subsidiary head to be used at the end of the irrigating season. The former should be the longer of the two, so that it may drop most of its silt above the junction and thus not block the subsidiary. The latter should have its head well "boxed" by side banks so that flood water may not enter it (Art. 204 (*d*), p. 415). Some engineers consider subsidiaries useless, but occasionally they are of great value in saving crops.

24. *Canal Embankment* (*p.* 479).—For the length in which the canal is within the river's high-flood margin it should be protected on its river side from the ingress of flood water by a flood-embankment. Such a bank will thus be wetted on both sides and distributaries will not be led through it, but arrangements should be made to keep this section of the canal (if it is in excavation) full of water during floods so as to prevent it from acting like a borrow pit in increasing the infiltering head (Art. 196 (*b*), p. 385). If an embankment is also required on the land side of the canal, it will be of less height and may have distributaries led through it.

25. *Pitching of Canal Section* (*p.* 508).—"Roughened pitching" of the canal section at cross-drainage works, or below

these, may be formed by constructing one-sixth of the area with bricks projecting half their length so as to lessen eddying motion of the water. If the reduced section of a channel is continued with a pitched surface, the scour of the bed and sides downstream will follow such extension despite such roughening: the pitched extension should therefore gradually be widened out to full section to prevent this.

26. *Corrosion by Rusting* (*p.* 510).—It is held by some that the rust first formed on the embedded steel or iron will unite with the cement or lime to form a protective skin which will be water- and air-tight and will thus prevent further corrosion. This may be true, but it may not, as rust during its formation expands and thus renders the junction more porous, while the infiltering water will be under pressure and charged with air which may lead to further rusting. Until prolonged experience proves which is the correct view, it does not seem advisable in important works to adopt metallic re-inforcement where repairs to it cannot easily be effected. (See p. 157, para. (*c*) and p. 295, para. (*b*)).

27. *Design of Distribution Channels* (*p.* 520).[1]—A major distributary may be considered as one with a discharge of more than 40 cusecs and a minor distributary as one with from 8 to 40 cusecs discharge. A water course may be as much as 3 miles long, but the shorter it is the better if it is not under supervision for maintenance. All channels should be aligned as centrally as possible in respect to their command so far as ridge lines permit. The main canal and its larger branches may be aligned at their heads without great reference to the level of the country as direct irrigation does not take place from them: their alignment should be chosen chiefly so as to equalise excavation and embankment. Minor distributaries should, as a rule, be taken off from major ones and water courses from them. If absolutely necessary, the resulting loss of command may be made good by a low weir built across the larger channel below the off-take of the smaller one.

As few outlets as possible should be constructed on the larger channels: this is partly to avoid possible danger from them, and, partly, to prevent fraudulent regulation by the petty staff or by the cultivators themselves. The difficulty of determining the size of an outlet is due to the variations of the duty caused by differences in soil, crops, lengths of field channels and times of closure. To increase the duty the supply should be restricted as much as possible. For simplicity in duty calculations it may be assumed that the number of seconds in a day (86,400) is twice the number of square feet in an acre (43,560).

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[1] "Irrigation Works," by E. S. Bellasis, M.Inst.C.E., E. & F. N. Spon, 1913.

One channel should, as a rule, not tail into another. The advantage of adopting such a course is that thus the tail of the first channel can be made larger as surplus water in it can be utilised. The disadvantages, which are greater, are that the tailing channel runs too close to the one it joins, thus interfering with irrigation, and that gauging of the discharge utilised by the former is difficult.

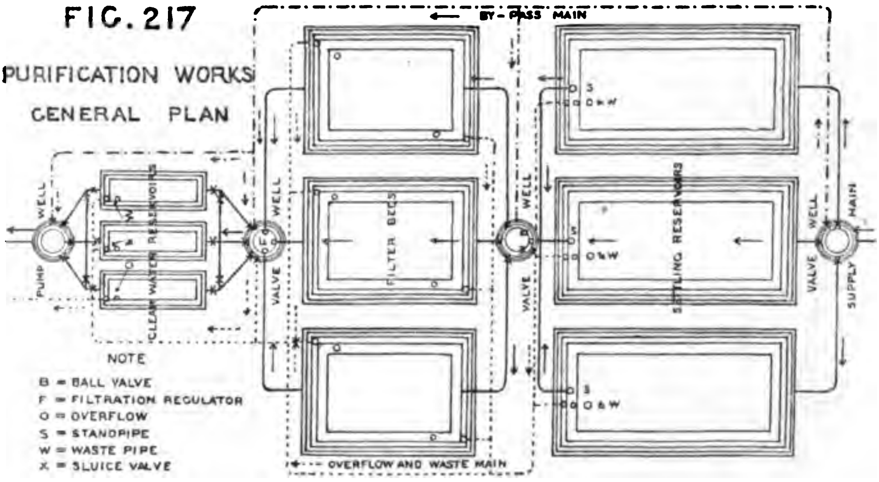
In the Punjab the gradient varies from 1 in 8,000 for main canals to 1 in 2,000 at the tail of distributaries; in boulder beds it may be 1 in 1,000. The mean velocity in feet per second is from 3 to 4 (occasionally 5) in main canals, and in distributaries from 1 to 2. The velocity is calculated by means of Kutter's formula; the coefficient used for new and smooth, well-maintained channels is 0·020, and for old, rough, and badly-maintained ones, 0·025. Embankment side slopes are usually at 1½ to 1, and excavation ones at 1 to 1. The top width of channel banks varies, in accordance with their size and the nature of the soil, from 20 to 3 feet; their free-board above full-supply level is from 2 to 1 foot. The full-supply discharge of main channels varies from 12,000 to 50 cusecs and the full-supply depth from 12 to 3 feet. The full-supply level of minor channels is kept a little below that of the major ones from which they draw off so that the former may get their designed discharge when the supply of the latter becomes low. The usual ratios of discharge to bed-width are—

Discharge, cusecs ..	10	25	100	200	500	1,000
Ratio	3·5	4	4·5	5	6	6

28. *User of Water-rights* (*p.* 535).—A somewhat similar mining law is in force for derelict lead mines in the Peak district of Derbyshire. Every lead mine there is recorded in the archives of the Barmaster of the Soke in which it lies. When a claim is made to a disused mine, the Barmaster notifies the fact, and unless the last owner begins work within twenty-one days, the mine passes to the new claimant on payment of certain fees.

29. *General Arrangement of Purification Works* (*p.* 587).—Fig. 217 gives a typical arrangement of these works when it is practicable to place all together at one site; frequently, however, it will be necessary to locate the sets of basins at different sites. Should coagulating basins be installed, they would be formed downstream of the settling reservoirs. By the arrangement shown any chamber can be brought into, or thrown out of, action, and the supply passed through the installation by the supply main or outside it to the pumps direct by the by-pass main

FIG. 217

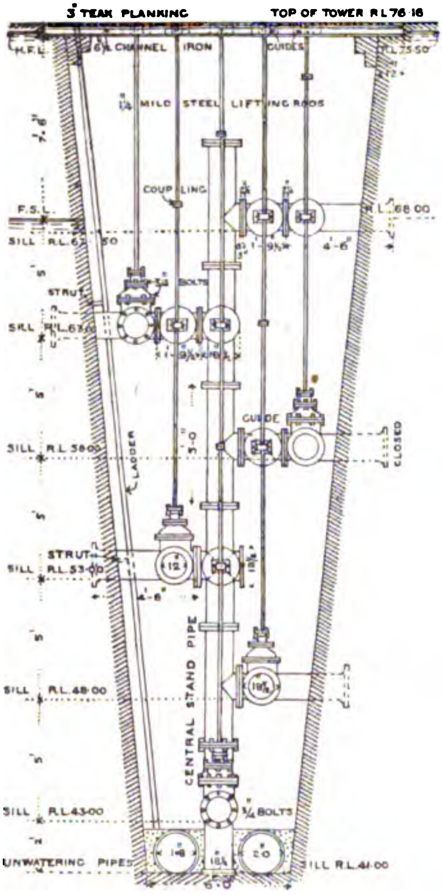


30. *Waterworks Outlet Tower* (*p.* 597).—Fig. 218 illustrates the outlet of the Hubli Water Works, Bombay Presidency. The water can be drawn off at different levels through five pipes, each controlled by a valve inside the tower, and communicating with a central stand pipe common to them all from which the main to the town is led. Downstream of the stand pipe is a sixth valve which thus gives double control of the others. Upstream of the tower is an inspection inlet chamber pierced by a sluiceway regulated by a simple sluice, which, when the water surface falls below the top of its walls, gives triple control of the two lowermost water supply pipes in the tower. This sluiceway also allows discharge to pass to two unwatering pipes fitted with independent valves outside the tower which are opened when water has to be run to waste to

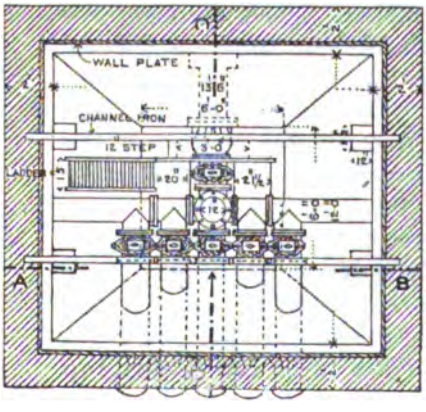
FIG. 218

OUTLET TOWER

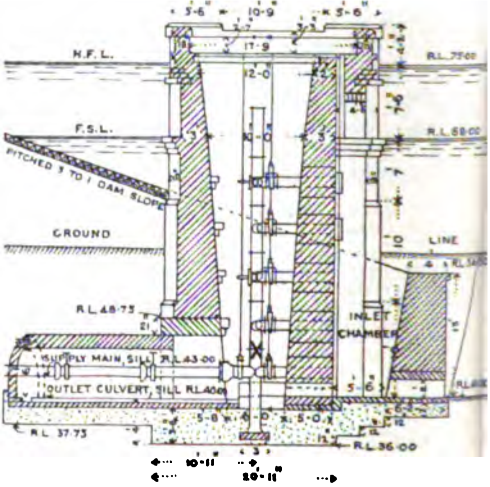
SECTION ON AB



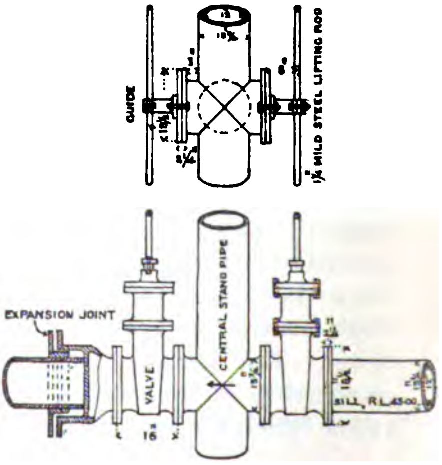
PLAN



SECTION ON CD (RED^D)



DETAIL AT X



lower the reservoir level. The internal sluices and the guides for their lifting rods are carried by pipe bearers of as few patterns as possible with their outer ends embedded in the masonry of the tower. The inlet ends of the supply pipes are formed as bellmouths protected by gratings over which tarpaulins can temporarily be placed to shut off supply when the valves inside the tower have to be examined.

31. *Re-inforced Cement Pipes* (*p.* 618).—Such pipes under the Hume patent were originally made in Australia and are now being introduced into other countries. It is claimed for them that compared with cast-iron pipes they have the advantages of lower cost, increased durability, simplicity in manufacture and greater speed in production.

32. *Slipperiness of Tarred Roads* (*p.* 783).—Owners of horses in England object strongly to tarred roads as their slipperiness causes distress and damage to their animals and possible danger to riders and drivers. To prevent slipperiness a combined strip pavement consisting of alternate lines of hard, short-fibred Australian jarrah and of soft, long-fibred red pine has been laid; it is said that its life is longer than that of pavements made entirely of either of these woods. Apparently this is on the principle of the elephant's tooth (p. 731). Another development is to have not only a concrete foundation (which may be strengthened by metal reinforcement and then reduced in thickness), but also a concrete surface. If this proves successful, it should be suitable to conditions in the tropics but its cost will be considerable.

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